Fine grained sediment clean-up in a modern urban environment

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Abstract

Fine grained sediment deposition in urban environments during natural hazard events can impact critical infrastructure and properties (urban terrain) leading to reduced social and economic function and potentially adverse public health effects. Therefore, clean-up of the sediments is required to minimise impacts and restore social and economic functionality as soon as possible. The strategies employed to manage and coordinate the clean-up significantly influence the speed, cost and quality of the clean-up operation. Additionally, the physical properties of the fine grained sediment affects the clean-up, transport, storage and future usage of the sediment. The goals of the research are to assess the resources, time and cost required for fine grained sediment clean-up in an urban environment following a disaster and to determine how the geotechnical properties of sediment will affect urban clean-up strategies. The thesis focuses on the impact of fine grained sediment (<1 mm) deposition from three liquefaction events during the Canterbury earthquake sequence (2010-2011) on residential suburbs and transport networks in Christchurch. It also presents how geotechnical properties of the material may affect clean-up strategies and methods by presenting geotechnical analysis of tephra material from the North Island of New Zealand. Finally, lessons for disaster response planning and decision making for clean-up of sediment in urban environments are presented.

A series of semi-structured interviews of key stakeholders supported by relevant academic literature and media reports were used to record the clean-up operation coordination and management and to make a preliminary qualification of the Christchurch liquefaction ejecta clean-up (costs breakdown, time, volume, resources, coordination, planning and priorities). Further analysis of the costs and resources involved for better accuracy was required and so the analysis of Christchurch City Council road management database (RAMM) was done. In order to make a transition from general fine sediment clean-up to specific types of fine disaster sediment clean-up, adequate information about the material properties is required as they will define how the material will be handled, transported and stored. Laboratory analysis of young volcanic tephra from the New Zealand’s North Island was performed to identify their geotechnical properties (density, granulometry, plasticity, composition and angle of repose).

The major findings of this research were that emergency planning and the use of the coordinated incident management system (CIMS) system during the emergency were important to facilitate rapid clean-up tasking, management of resources and ultimately recovery from widespread and voluminous liquefaction ejecta deposition in eastern Christchurch. A total estimated cost of approximately $NZ 40 million was calculated for the Christchurch City clean-up following the 2010-2011 Canterbury earthquake sequence with a partial cost of $NZ 12 million for the Southern part of the city, where up to 33% (418 km) of the road network was impacted by liquefaction ejecta and required clearing of the material following the 22 February 2011 earthquake. Over 500,000 tonnes of ejecta has been stockpiled at Burwood landfill for all three liquefaction inducing earthquake events. The average cost per kilometre for the event clean-up was $NZ 5,500/km (4 September 2010), $NZ 11,650/km (22 February 2011) and $NZ 11,185/km (13 June 2011). The duration of clean-up time of residential properties and the road network was approximately two to three months for each of the three liquefaction ejecta events; despite events volumes and spatial distribution of ejecta. Interviews and quantitative analysis of RAMM data revealed that the experience and knowledge gained from the Darfield earthquake (4 September 2010) clean-up increased the efficiency of the following Christchurch earthquake induced liquefaction ejecta clean-up events.

Density, particle size, particle shape, clay content and moisture content, are the important geotechnical properties that need to be considered when planning for a clean-up method that incorporates collection, transport and disposal or storage. The geotechnical properties for the tephra samples were analysed to increase preparedness and reaction response of potentially affected North Island cities from possible product from the active volcanoes in their region. The geotechnical results from this study show that volcanic tephra could be used in road or construction material but the properties would have to be further investigated for a New Zealand context. Using fresh volcanic material in road, building or flood control construction requires good understanding of the material properties and precaution during design and construction to extra care, but if well planned, it can be economically beneficial.

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Chapter 1. Introduction

1.1. Context of Study

Cities are centres for development, prosperity, innovation, and will soon be home to two thirds of the global population (World Bank 2013, WHO, 2013). However the dense concentration of people and increasingly high dependence on infrastructures can significantly increase vulnerability to disasters (Chester *et al.*, 2001, NHR, 2007).

Critical infrastructures, or lifelines, are essential elements in the functioning of a society and its economy. They include (Wilson et al, 2012, Platt, 1991):

- Electricity generation, transmission and distribution;
- Gas and oil production, transport and distribution;
- Telecommunications;
- Water supply (drinking water, waste water/sewage disposal, stormwater and drainage networks);
- Food production and distribution
- Heating (e.g. natural gas, fuel oil, district heating)
- Transportation systems (road and rail networks, airports, ports, inland shipping).

Damage and disruption to lifelines utilities can have significant and widespread impacts on communities affected by disaster because of their interdependencies (NHR 2007, Yu 2010). Lifeline services are critical for both emergency response and the local community (Tierney and Nigg, 1995).

Effects of disasters on cities will depend on exposure and vulnerability of each asset and includes (Albala-Bertrand, 2003):

- Injuries and loss of lives,
- Residential and infrastructure damage and destruction
- Local economy

Disaster can causes impact through a variety of different hazards. One hazard, which has not been frequently studied, is the deposition of fine grained (<1mm) sediment in urban areas, such as flood silt, volcanic tephra fall, landslide debris, or liquefaction ejecta following strong earthquake shaking. Fine grained sediment (<1 mm) deposition in urban environments is known to impact lifelines and properties leading to reduced social and economic functionality. Furthermore it can impede post-disaster rescue and repair operations and can potentially have negative public health effects (Johnston *et al.*, 2001, Giovinazzi *et al.*, 2011, Plumlee *et al.*, 2012, UNOCHA, 2011). Therefore, clean-up of the sediments is required to minimise impacts and restore social and economic functionality as soon as possible. Planning for the clean-up of urban areas (transport network and residential-commercial-public spaces) following a disaster should be a priority especially for New Zealand, which has a complex hazardscape including earthquakes, tsunami, landslides, flooding, volcanic eruption, storms, and more.

1.1.1. Disaster Management

Landscape alterations by natural processes have been occurring on Earth for billions of years. Humans have been building communities and cohabiting with those natural processes for centuries. Natural systems become hazards when they threaten human values such as lives and/or infrastructure. Disasters occur when serious disruption of the functioning of a community exceeds the ability of the affected community (ISDR, 2009).

A disaster risk management cycle has been used to describe the different stages around a disaster (NHR, 2007) (Figure 1). Four major stages (commonly known as “The 4Rs”) are identified by; Response, Recovery, Reduction (Mitigation) and Readiness (level of preparedness) and are describe below (NHR, 2007):

The response phase directly follows the disaster and aim to minimize the impacts of the hazards. It will generally include evacuation and relocation, search and rescue efforts, initial damage and needs (support required) assessment, and initial repairs.

The recovery phase follows the response phase and can be of various lengths. It includes all activities related to the community returning to a normal and functioning state. It will include activities such as clearing the rubble and debris, detailed damage and needs assessment, temporary housing, repairs, reconstruction, disaster risk reduction operation and monitoring.

The reduction or mitigation phase aims to eliminate or reduce the effects of disasters. This is done through risk hazard analysis and implication of risk reduction strategies such as building codes, research on lifelines vulnerabilities, land use planning and public education.

The readiness or preparedness phase consists of planning for future disaster. It aims to facilitate and increase the effectiveness of the response to minimise the impacts of the disaster. This includes staff training, implementation of warning system, response plans, evacuation plans and public education. This is also the phase where further research should be undertaken to increase understanding of hazards and disaster management.

FIGURE 1: DISASTER RISK MANAGEMENT CYCLE (THE 4RS)

In summary, the common goals of all disaster management are (NHR, 2007):

- to reduce, or avoid, potential losses from hazards
- assure prompt assistance to victims
- achieve rapid and effective recovery through readiness

Disaster management achieves these goals through various techniques. It can be done through the use of a common framework that provides a systematic approach to reduce risk (Figure 2). A keypart of this approach is to identify challenges from past events and using lessons to prepare for them (NHR, 2007).

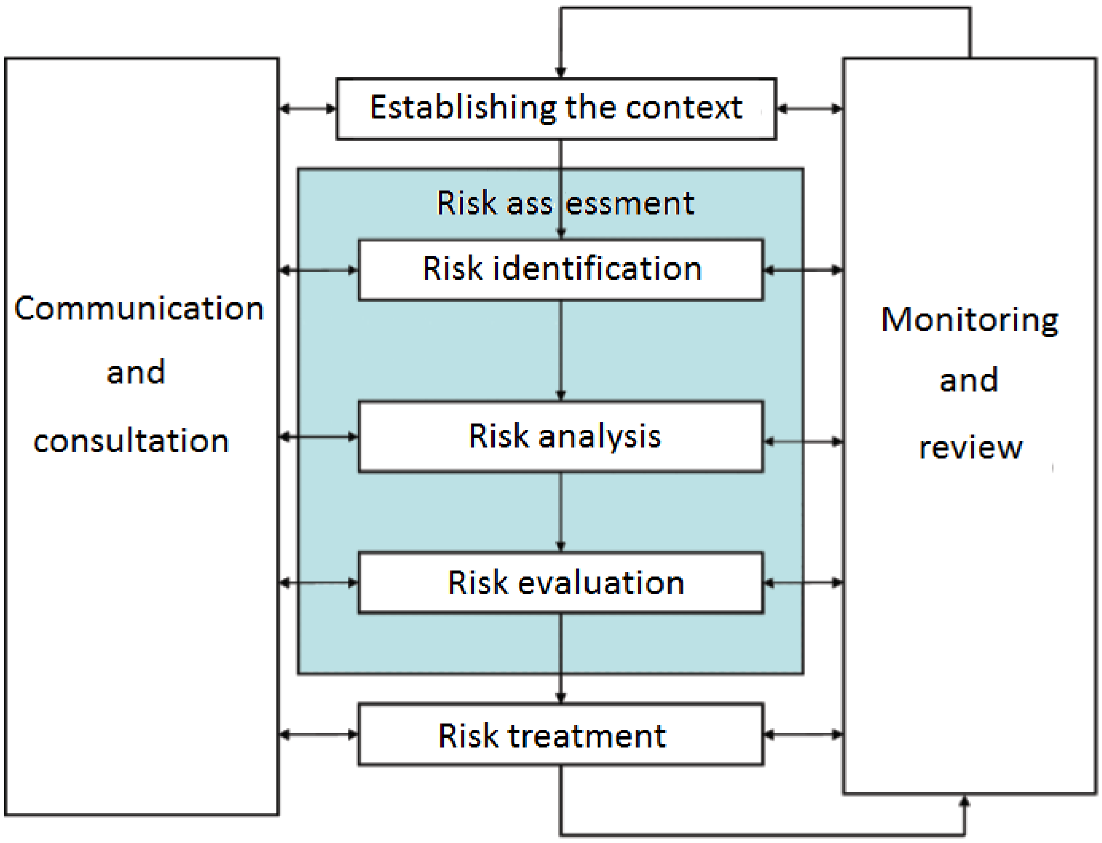

Figure 2: Risk management framework (Source: New Zealand Standards, 2009)

1.2. Aims and Objectives

This research focus on the impact of fine grained deposition following a disaster from residential suburbs and transport networks. The goal is to assess resources, time and cost required for fine grained sediment clean-up in urban environment following a disaster. The results aims to minimise the consequences of disasters by identifying the challenges of cleaning-up an urban environment following a disaster. This is part of the reduction and readiness stages of the 4r's. The objectives for this research are:

- Review the consequences and clean-up of deposition in urban environment.
- Identify the likely geotechnical properties of fine grained deposition looking at:
    - Christchurch liquefaction silt (Canterbury earthquakes 2010-2011) and
    - volcanic tephra (young eruptions from North Island of New Zealand).
- Investigate the management, logistics, resources, volumes, time and financial costs needed to conduct a large-scale clean-up operation in urban areas following a disaster based on the Christchurch earthquake sequence liquefaction clean-up case study.
- Quantify the Christchurch liquefaction silt clean-up and identify trends that can be used to estimate the resources needed, time and possible cost of clean-up for an urban environment following fine grained sediment deposition.

1.3. Research Methods

Various methods used to execute the different objectives of the thesis include:

- Review of relevant literature
- Semi-structured interviews with key members from major organisations responsible for the clean-up of the city following the Christchurch earthquake sequence (2010-2012).
- Laboratory testing performed on volcanic tephra samples collected from the North Island of New Zealand) to determine geotechnical properties:

    - Atterberg limits (penetration cone for the plasticity index/plastic-liquid limit)
    - Particle size distribution (lazer sizer and sieve)
    - Density (In situ/ reconstituted and dry versus wet)
    - Angle of repose
- Data filtering and analysis
- Statistical analysis
- Spatial and temporal analysis

A detailed description for each method is presented in their related section.

1.4. Thesis Outline

The thesis is structured into six chapters presented in Table 1.

TABLE 1: THESIS OUTLINE

Chapter	Title	Purpose
1	Introduction	Present the context behind the research, the aims and objectives of the project, a brief overview of the method used and present the thesis structure.
2	Literature review	The purpose of this chapter is to review fine grained sediment clean-up in urban environments and identify the similarities and differences. It presents how the sediments are formed, their dispersal capacity, their impact to critical infrastructure and how they compare and relate. This is part of the risk identification stage within the management framework.
3	Liquefaction clean-up in Christchurch: Qualitative study	This chapter present the qualitative analysis of the liquefaction silt clean-up in Christchurch following the 2010-2012 Canterbury earthquake sequence. This is part of the readiness section.
4	Liquefaction clean-up in Christchurch: Quantitative study	This chapter present the quantitative analysis of the liquefaction silt clean-up in Christchurch following the 2010-2012 Canterbury earthquake sequence. This is part of the readiness section.
5	Fine grained material properties	This chapter present the results from laboratory testing on tephra samples from the North Island of New Zealand and compares them to other values found in the literature. This was done to investigate how the geophysical properties of fine grained sediment can affect the clean-up strategies based on tephra samples properties from the North Island of New Zealand.
6	Discussion and Conclusions	This section presents a summary of the main thesis findings, the conclusion and recommendation for future work.

Chapter 2. Literature Review

2.1. Introduction

The purpose of this chapter is to review fine grained sediment clean-up in urban environments. It will introduce urban and disaster waste clean-up management as well as present the benefits and management issues related to volunteerism during disasters. It will then present a general description of common fine grained sediment deposited by natural hazards by describing their origin and depositional processes, identify how they impacts lifelines and common strategies and resources required to clean-up the material. It will also discuss volunteer management following a disaster. This is part of the risk identification stage within the risk management framework (see Figure 2).

2.2. Urban Sediment Clean-up

This section presents a general overview of street cleaning in an urban environment and then presents urban cleaning following a disaster.

2.2.1. General Urban Clean-up

The urban conditions of the Middle Ages are notorious for having been unsanitary as there were no closed sewers, wastes were disposed of directly into the street and there were no authorities in charge of cleaning the streets (Thorndike, 1928). The rapid growth in urban environment and urban population density that arrived during the pre- and early industrial period required the clean-up of the city from unwanted waste (natural and manmade). Unwanted waste removal became essential as the unsanitary conditions and overcrowded urban areas facilitated the spreading of infectious diseases (Perdue *et al.*, 2003). In modern day complex urban environments, cleaning systems needs to be organized with well-planned schedules and operation protocols for removing sediments and debris from the streets efficiently. Modern street cleaning is generally performed for three main reasons (Brinkmann and Tobin, 2001):

- storm water pollution reduction (protecting natural water bodies from contamination from pollutants generated by human activity),
- urban cleanliness and
- aesthetic consideration.

Street sweeping management is complex. It requires (Brinkmann and Tobin, 2001); the identification of the problem source (physical system or human use system), identification of the size and density of the urban environment, characteristics of the waste, knowledge of governmental policies and water quality standards, funding, management of the waste and more. Brinkmann and Tobin (2001) present a framework to facilitate street sweeping practices and the identification of their impacts.

Great volume of waste is collected by street cleaning and dumping costs may be expensive. Therefore, management of street sweeping waste needs to consider recycling and reuse potential of the material as well as specific treatment for contamination waste.

Most of the constituents of urban waste consist of native material and organic matter (leaves and grass), but there is a chance that it contain metals, nutrients and organic chemicals (Brinkmann and Tobin, 2001). The fine particles found on roads carry metals and hazardous organic chemicals. If not collected during street sweeping, they will enter the storm water systems and impact the surrounding natural waterways. Management of street sweeping waste needs to take into consideration their recycling and reuse potential as well as possible contamination needing special treatment. It will generally involve a landfill to collect all the material cleaned from the streets and when the material is considered contaminated and hazardous it would have to be stored in a site that can contain it. Street cleaning produces a great volume of material and the cost of dumping can be expensive especially if it is required to be disposed of in a landfill to contain toxic materials.

The frequency of the cleaning additionally needs to be managed, as empirical studies suggest regular street sweeping reduces storm water pollutants (Brinkmann and Tobin, 2001).

Street sweepers are expensive and they do not perform well for every type of material. There are three major types of street sweepers used in the United States and their characteristics are presented in Table 2 (Brinkmann and Tobin, 2001). Rotary brushes are more efficient for general use while vacuum sweepers are better at removing fine particles which transport pollutants. Some new models incorporate the two techniques and include the addition of water sprayers that loosen the particles, increasing the quantity of fines that can be collected by the brooms and vacuums. It is important to assess the needs of individual communities and identify the specific levels and types of pollutants present for different land zones (residential, commercial or industrial) when planning urban street sweeping.

TABLE 2: COMMON STREET SWEEPERS USED IN ROAD CLEAN-UP AND A DESCRIPTION OF THEIR AND USAGE

Sweeper type	General characteristics	Best usage
Mechanical rotary brush sweepers (broom sweeper)	Physical brushing mechanism Relatively inexpensive The most common sweeper available, produced by many companies and thus, is easy to maintain and replace parts Small storage capacity	Efficient at picking up coarser-grained sediments and general street debris (soil sediment, grass clipping, leaves, some litter) Can leave behind small quantities of fine particles.
Vacuum sweeper	Air pressure mechanism Less common	Best for picking up fine grained material and removing pollutant Not efficient for coarser material
Combination sweepers	Combination of brush and vacuum sweeper Expensive	Effective at removing a wide range of particles

2.2.2. Disaster Waste Clean-up

Disasters are capable of generating large volumes of waste and debris; in extremely short periods, equivalents of 15-20 years' worth of a community's normal solid waste production may be generated from a disaster (Brown *et al.*, 2011). This can severely stretch waste collection and management resources in the aftermath of a disaster. Recent disasters in New Zealand and internationally highlight that disaster waste management is a critical element for lifeline organisations and municipalities to consider in disaster management plans. A recent study by Brown *et al.* (2011) found that:

- The large volume of solid waste generated after a disaster has the potential to overwhelm day-to-day solid waste operations, create public and environmental health issues and result in years of disruption.
- Disaster debris can impede rescuers and emergency services from reaching survivors.
- Double handling of waste, uncoordinated organisations, legal hurdles, poor quality control, poor communication, or poor funding mechanisms can each lead to higher costs for collection, treatment and disposal of disaster wastes.
- The slow management of solid waste can also impede economic recovery by inhibiting rebuilding activities and lead to significant community frustrations.

Disaster waste commonly includes building debris from collapsed or demolished buildings, but may also include large volumes of fine grained sediment deposited by natural hazards such as liquefaction ejecta, flood silt, landslide/mudflow debris or volcanic tephra fall (Appendix A and B). Disaster debris can contain hazardous materials and therefore poses a significant threat to the environment and to human health (Plumlee *et al.*, 2012).

Based on past disaster waste management experiences, The United Nations presented good practice guidelines to minimise adverse impacts to health, safety and environment caused by disaster waste. The major issues and impacts from disaster and their wastes are presented in Appendix C.

2.3. Volunteer Management

Volunteerism in disaster risk reduction can significantly aid an affected community but it has also proven to complicate the response when the management teams are not ready to receive them (Fernandez *et al.*, 2006). Table 3 presents a summary of benefits and issues highlighted by Fernandez *et al.* (2006) from multiple case studies. The table shows, if well managed; volunteers are valuable resources during an emergency situation and should be considered in the clean-up plans of fine grained sediment deposition following a disaster.

TABLE 3: BENEFITS AND ISSUES OF VOLUNTEER DURING A DISASTER. SOURCE: FERNANDEZ *ET AL.* (2006)

Benefits	Limitations
• Significant manpower resource (time, skills, and abilities) • Can save lives • Augment emergency staff with basic skills and support activities • Allow responders to focus their efforts on specialized work • Providing lacking skills • Economic advantages • Helpful to disaster victims (reduce stress, is an outlet for rage, as part of the healing process, empower victims)	• Can hinder disaster response • Can create health, safety, and security issues • Can distract responders from their duties • Can interfere with response operations. • Can be ineffective if organizations and management systems have not prepared for volunteer resources. • Require logistic support (food, shelter, protective equipment) • Can cause road congestion

2.3.1. Volunteer Background

A volunteer is defined as a person who freely offers to take part in an enterprise or undertake a task (Oxford dictionary). This behaviour has been seen throughout time.

During a disaster, the need to help others is even more present within the affected communities. Studies on citizen participation following a disaster focus on why people volunteer and what is driving spontaneous action and convergence to help.

Large scale volunteer response after a disaster, either from trained or general public, can be called “convergence” (Fritz and Mathewson 1956; Fernandez et al. 2006). It is defined by Fritz and Mathewson (1956) as an “informal, spontaneous movement of people, messages, and supplies towards the disaster area”. This “convergence” behaviour has been observed throughout history from the Halifax shipping explosion in 1917 (UVa, 2012), the Loma Prieta earthquake in California (O’Brien and Mileti, 1992) to the latest and more recently, the earthquakes in Christchurch (2010-2011) (Villemure *et al.,* 2011).

Fritz and Mathewson (1956) present a well-documented list of examples showing the traffic problem associated with convergence, necessitating centralised authorities to devote significant human resources to control and direct volunteers, which distracts and obstructs their core emergency response and management roles.

Various studies have shown that volunteers can have a significant positive impact on disaster victims by reducing stress and providing guidance throughout their victims healing process (Fernandez *et al.,* 2006). They also have significant benefits for the response. It has been shown that most of the important response activities are performed by spontaneous volunteers until the trained authorities arrive, such as search and rescue. For example, volunteers were responsible for all lifesaving in 1978 when a showboat ‘Whippoorwill’ was struck by a tornado on Lake Pomona (Kansas) and capsized (Drabek, 1981; Kilijanek, 1980) from Auf der Heide, 1989). However, it has also been identified that spontaneous volunteerism represents a significant management problem for an organisation that is not prepared to receive volunteers. This can lead to major ineffectiveness of the response operations if valuable time is spent organising the volunteer efforts while it is more valuable close to the event where injured persons need immediate assistance (Fernandez *et al.* 2006). In extreme circumstances spontaneous volunteerism may generate such a large quantity of resources that it actually impedes the affected community if it exceeds the required need or if it is not necessary (Auf der Heide, 1989). The importance of communicating the actual needs to emergency management organisations is therefore primordial to avoid this surplus that can impede and complicate disaster response.

The attack on the World Trade centre on September 11th 2001 was one of the most tragic disasters in the American history. Spontaneous volunteerism and motivations following the attack on the World Trade centre on September 11th 2001 was studied by Lowe and Fothergill (2003). Large-scale convergence on the disaster site caused by the attack was also studied by Kendra and Wachtendorf (2002); Lien (2002); National Academy of Sciences (2002). Lowe and Fothergill performed a series of interviews with key volunteers to understand their motivations to volunteer. This research showed that service organizations were overwhelmed by volunteer demand; numbers from the Red Cross showed that approximately 22,000 volunteer offers were received after two and a half week of the tragedy. Interviewed volunteers talked about frustrations generated by unorganised coordination efforts and unclear information about the needs of the response. Lowe and Fothergill (2003) research showed that despite the frustration from the lack of coordination and bad management, spontaneous volunteerism had major positive impacts on the affected community. Benefits were large for the volunteers themselves who evolved from passive victims to “active participants”, bringing positive outcomes in this negative event.

Other studies on disaster behaviour present a misconception showing that the authorities will have to manage and control a panic and evacuation situation while contrarily, most case study shows it is more likely to manage convergence (Fritz and Mathewson, 1956).

2.4. Fine Grained Sediments

Fine grained sediment deposition in urban environments is known to impact critical infrastructure and properties (urban terrain) leading to reduced social and economic functionality and potentially public health effects (Plumlee *et al.,* 2012). Therefore, clean-up of the sediments is required to minimise impacts and restore social and economic functionality as soon as possible. This section will present a general description of common fine grained sediment deposited by natural hazards; volcanic tephra fall, liquefaction ejecta, flood silt and snow fall. It describes their origin, processes and properties as well as how they impact lifelines and how they are managed. Snow fall clean-up was included to support clean-up management and strategies.

2.4.1. Tephra

Volcanic tephra is a term use to include all size of explosive volcanic debris fall (USGS, 2009a) (Table 4). Tephra fall is a major hazard from explosive volcanic eruptions. It can be dispersed over very large distances, affecting large areas. Tephra dispersal is controlled by the wind velocity, wind direction and eruption style; which includes the explosivity of the eruption, volume of ejected material and the size of the particles ejected. Wind varies with elevation, thus depending on the eruption column height, tephra dispersal will be different. Tephra particles are typically hard, abrasive, mildly corrosive, electrically conductive when wet, and fine grained deposits can be immiscible (USGSa, 2010).

The grain size of the tephra varies widely between single eruption and between different eruption styles. Tephra from basaltic eruptions have small proportions of very fine tephra (~1 to 4%) compare to silicic eruptions (30 to 50%) (Rose and Dorant, 2009). Particle grain size from a phreatomagmatic eruption (eruptions formed from the interaction of magma or lava with an external source of water ranging from submarine, groundwater and glacier to crater lakes resulting in an explosive eruption) are finer and better sorted (Morrisey, 2000). In general, grain size and variety of grain size both decrease with distance to the source. Tephra has three principal component; volcanic glass, mineral/crystals and lithics. The proportion of those components will vary with eruption style and eruptibility. Volcanic glass is formed by rapid cooling of juvenile/fresh magma, minerals and crystals are formed within the magma before the eruption and will vary depending on the magma composition and evolution (Appendix D1), lithics are rock fragments that represent the volcanic edifice or surrounding lithologies that were scraped off during the eruption.

Tephra density is dependent on the particle bulk density, the grain size and shape, its composition, compaction and moisture content. Appendix D2 present particle densities of various component of a tephra fall deposit. The density of the fall deposit will be dependent on the occurrence of each component.

Tephra fall has the potential to cause significant damage and disruption within affected urban environments (Table 5) (GNS, 2010). Clean-up of tephra is important to restore transportation to permit emergency response, evacuation and access to lifelines utilities for repair. The ongoing remobilisation of tephra through wind and water can cause continuous and serious damage to utilities such as stormwater and sewage pipelines (Johnston *et al.*, 2001). Fine particles of tephra can also contaminate buildings and houses interior, potentially damaging essential furniture. A fast and efficient clean-up is necessary to minimise disruption from tephra and the restoration of the impacted area.

Only few previous study on tephra fall clean-up has been published, but removing, transport and disposal of volcanic tephra is a hard, time consuming and costly challenge (USGSa, 2010). Some basic guidelines on strategy and prioritization of tephra removal have been published by Johnston *et al*. (2001), but the management of tephra removal for individual localities has been identified as an important future research topic. The clean-up management of a large urban area such as Auckland necessitate significant operational resources and planning. The restoration of road network to permit the access to emergency infrastructures such as hospitals and areas where assistance is needed are priorities during a crisis and thus the removal of unconsolidated fine grained sediment (<1 mm) such as tephra fall following a volcanic eruption is a valuable research topic. In order to limit damage and restore a city affected by volcanic tephra, an effective and strategic clean-up must take place.

TABLE 4: CLASSIFICATION OF VOLCANIC PYROCLASTICS. SOURCE SCHMID 1981

Grain size	Name
> 64mm	Blocks and bombs
2 – 64 mm	Lapilli
< 2 mm	Ash grains
< 1/16 mm	Dust grains (or fine ash grains)

Before the 1980 eruption of Mount St-Helens, there was little documented knowledge on how to remove tephra fall in downwind communities (Johnston *et al.,* 2001). Contractors in charge of cleaning the roads in Yakima, Washington State, were not prepared but eventually managed to develop an effective plan (Johnston *et al.,* 2001). Since then, a number of urban areas have been affected by tephra fall, requiring clean up. Wardman *et al.* (2012) reported that Guatemala City received between 2-3 cm of tephra from Pacaya's eruption on May 27th, 2010, requiring clean-up to enable a fast access to critical affected lifelines. The clean-up of approximately 11,350,000 m^3 of tephra on 2,100 km of roads was organised by the municipality and the army. The clean-up started on the night of the eruption and lasted for 3 weeks costing approximately $US 0.2 million for heavy machinery hire alone.

These leads to the requirement for documenting guidelines for tephra fall clean up. Johnston *et al.* (2001) provides such a summary, where they state the coordination and prioritisation of the areas that need to be primarily cleaned is the first guidance step, followed by personal protection, limit the handling and frequent servicing of plant and machinery used. Coordination between the properties owners and the cleanup teams during the tephra collection is important. Prioritization needs to be implemented for the cleanup of roads and it should be based on restoring transport and access to emergency services and facilities.

TABLE 5: TEPHRA FALL HAZARD TO DIFFERENT CRITICAL INFRASTRUCTURE

Critical infrastructures	Possible effect
Transportation	Damage to roads, ports, airports, rails. Reduce visibility, road gets slippery and impassable. New Zealand airport has a zero tephra tolerance, tephra on runway will prevent takeoff and landing, airspace could be closed.
Utilities	Possible damage to infrastructure, disruption to services (electricity, gas, fuel, telecommunications, water).
Primary industries (agriculture and livestock)	Starvation of livestock and loss of vegetation if pasturage becomes significantly buried. Trees can be damaged by loading of tephra, branches can break and fall on lifelines utilities.
Structure (houses, industries)	Tephra loading will depend on multiple variables such as roof strength & span, roof slope, amount of tephra, density of tephra and/or water content of tephra. In most cases, collapse is unlikely. Most conventional residential buildings cannot resist loads of 7kN/m2 (Blong 2002) and will collapse completely.
Health	Respiratory problems, external irritation, indigestion and poisoning.

2.4.2. Liquefaction Ejecta

Liquefaction occurs when saturated, typically fine-grained, unconsolidated soils are subjected to an applied force (such as earthquake shaking) and the increase in pore pressure causes the soil to lose strength and behave like a liquid (USGSd 2012, Johansson 2000). The likelihood of the soil to liquefy will be affected by the looseness of the soil, the degree of cementing/clay between particles and the drainage restriction while the he amount of deformation that a soil will experience when being subjected to liquefaction is dependent on the looseness of the material, the depth, thickness and extent of the liquefiable layer and the ground slope (EERI, 1994). Liquefaction is more common on young and loose geological environment with high ground water levels such as Holocene delta, river channel, flood plain, aeolian deposits and poorly compacted fills. Figure 3 present the grain size distribution for liquefaction susceptibility of soils.

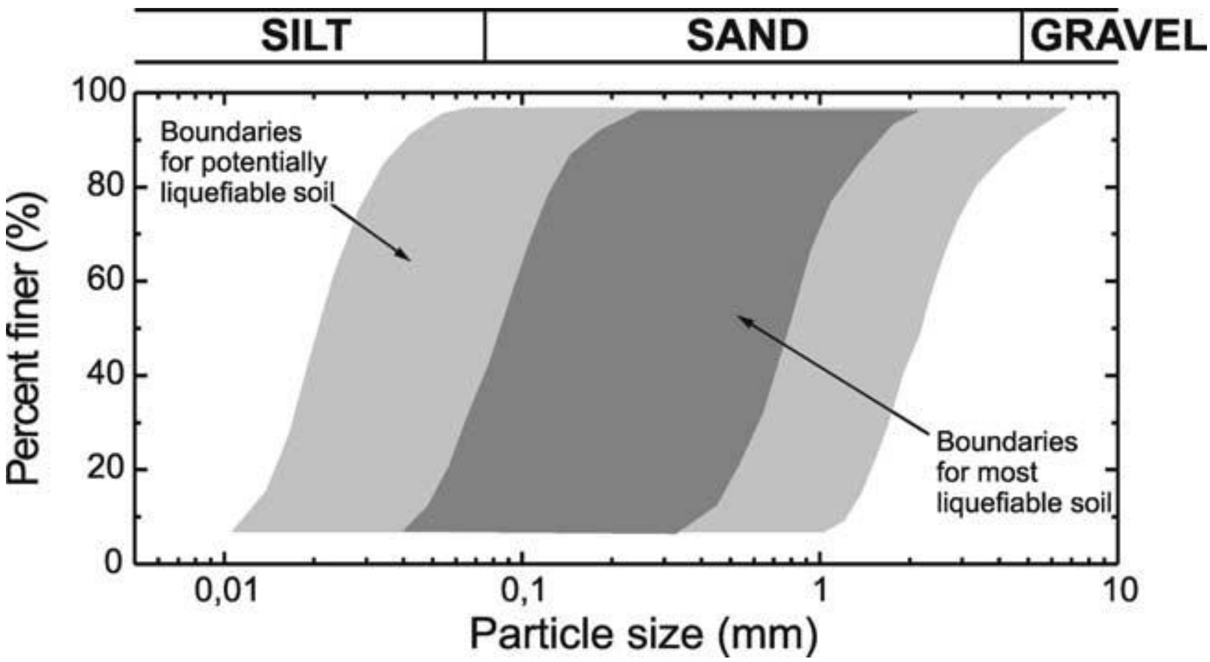

FIGURE 3: RANGES OF GRAIN SIZE DISTRIBUTION FOR LIQUEFACTION SUSCEPTIBLE SOILS BY (TSUCHIDA, 1970) FROM ALLA 2009

Earthquake induced-liquefaction has been observed all around the world and has the potential to impact large urban center. Cox *et al. (*2004) research showed that liquefaction is a frequent phenomenon that can be associated with many earthquakes and it can be used to identify past earthquakes. In fact, it has been observed in geologic record that the region of Southern Mississippi Embayment have experienced multiple large liquefaction field close to present day cities (Cox *et al.,* 2004). Earthquake induced liquefaction has also been observed in 1964 Niigata earthquake (Alaska, USA), 1868 Hayward earthquake (San Fransisco Bay Area, USA), 1989 Loma Prieta earthquake (San Fransisco Bay Area, USA), 1995 Great Hanshin earthquake (Kobe, Japan), 1999 Kocaeli earthquake (Izmit, Turkey), 2001 Peru earthquake (Arequipa, Peru), 2009 Sumatra earthquakes (Padang, Indonesia), 2010 Haiti earthquake (Port-au-Prince, Haiti) and 2010 Maule earthquake (central Chile) as well as in the 2010-2012 Canterbury earthquake sequence (Christchurch, New Zealand); (Kawasumi 1968, RMS 2010b, Boulanger *et al*. 1997, Kitagawa & Hirishi 2004, Ozcep & Zarif 2009, Hakam 2012, Audemard *et al*. 2005, RMS 2010a, Saragoni 2010). Liquefaction has caused important damage during those earthquakes to structural foundations and to infrastructures such as bridges and roads, interrupting traffic for restoration and response activities (Kitagawa, 2004).

This high frequency increases the potential for other urban area to be impacted in the future by liquefaction ejecta and thus, preparation for dealing with liquefaction ejecta is important has it has been identified as a potential risk in many large cities such as Wellington (New Zealand), Vancouver (Canada), San Francisco (US) (The Greater Wellington regional Council, Civil UBC, O'Rourke *et al.* 2006).

Earthquake induced liquefaction has been identified as the main reason for the damages to lifelines utilities, water distribution system, buried utilities, foundations, pipelines and sewers during the 1906 San Francisco earthquake, 1994 Northridge earthquake (California), within the Mendoza and San Juan provinces from 1861-1997 (Argentina), 1999 Kocaeli earthquake in Yalova Turkey, 2010-2012 Canterbury earthquake sequence (O'Rourke *et al*. 2006, Holzer *et al.* 1999, Perucca & Moreiras 2006, Ozcep & Zarif 2009, Wilson *et al.* 2011).

It has been well established that liquefaction causes damage to poorly design structural foundations and critical infrastructures such as bridges, roads and buried services (Kitagawa & Hiraishi 2004). However, earthquake engineers and emergency managers have paid less attention to the widespread ejection of fine-grained sediments at the surface during a liquefaction event. Such phenomena can cause significant disruption to transport infrastructure, storm- and wastewater networks, pose physical and mental health hazards for the exposed community and clean-up of the ejecta creates a significant demand on resources and time in a post-disaster environment (Sakr & Ansal 2012). Most research only mention the presence of liquefaction and structural damage caused by it, but there are no mentions of the clean-up of the sediment. It is important to know that street will be affected by liquefaction, making transport harder and clean-up necessary.

Despite the potential impacts and management issues, there have been no known previous studies which investigate the logistics, costs and strategies of liquefaction clean-up from an urban environment. An analogous study which investigates fine grained sediment clean-up from an urban environment is a study on volcanic tephra clean-up by Johnston et al, (2001). This study provides a pre-planning guide, prioritization list and best method for clean-up that can be used for tephra removal. It highlights the importance of coordination between the clean-up teams and the public.

Liquefaction can cause the ground to deform and have major impact on building foundation and buried infrastructures. It may cause flow failure, lateral spreading, ground oscillation and sand volcanoes and fill up widespread areas with removed sediment (USGSd, 2012).

2.4.3. Flood Sediments

Flood sediments can be caused by various processes ranging from heavy rain fall (Te Ara, 2008) and bad urban drainage, to catastrophic dam break flooding (Gallegos et al. 2009) and tsunami (Bird and Grossmand, 2011). Impacts of flooding and flood sediments to critical infrastructures are summarized in Table 6.

TABLE 6 : FLOOD HAZARDS TO VARIOUS CRITICAL INFRASTRUCTURES.

Critical infrastructures	Possible effects
Transportation	Damage to roads, collapse of bridges, traffic congestion, rail way and road closure blocking sections of highway, taking pavement with it in some places
Utilities	Possible damage to infrastructure, disruption to services (electricity, gas, fuel, telecommunications, water). Contaminated water
Primary industries (agriculture and livestock)	Damage to surrounding, forest, ridges, wild-life, zoo, urban community-trees, water bodies, shrubs, grass, fruit/vegetables in go down
Structure (houses, industries)	Water may infiltrate the building, big debris can damage. Range from water in the basement to destruction of the house. Structural damage, weakness, ceiling may collapse
Health	Immediate health impacts of floods include drowning, injuries, hypothermia, and animal bites. Flooding usually brings infectious diseases, e.g. military fever, pneumonic plagues, dermatopathia, dysentery, common cold, Dengue, break bone fever, etc. Chances of Food poisoning increases where electric supply interrupted in food-storage area due to flooding
Sources:	FitzGerald *et al.* 2010 GJ, Twigger-Ross, 2005, Molino, 2012., Yu 2010,

Study from Yu (2010) showed that majors sectors such as power, water, wastewater, healthcare and transportation are inter-dependent of each other and are vulnerable during flooding, with the power sector being the more severely impacted.

Flooding can cause contamination through remobilisation (Euripidou and Murray, 2004). Examples are oil spills from an oil refinery during the flooding caused by Hurrricanes Katrina and Rita in 2005 (Plumlee et al., 2012), and radioactively contaminated flood debris of the Tohoku earthquake induced tsunami (Japan, 2011) from the Fukushima Daiichi nuclear power plant (Bird et Grossman 2011, Shibata et al. 2012). Flood sediments can contain high levels of metals particularly marine origin flood sediment can contain high percentage of iron sulfides as seen in New Orleans, which risk of producing acid sulfates water with high metal concentration whit weathering when disposed outdoor (Plumlee et al., 2012, Shibata et al. 2012).

The clean-up will generally be conducted by the home owners or private clean-up companies SMH (2011). SMH (2011) provide a detailed guideline for cleaning flood impacted houses. It mentions that flooded building and houses presents hazards such as contamination, structure weakening, electric shock and explosion, requiring special precautions when handling. Use of disinfectant to sanitize contaminated surface and proper ventilation is recommended when cleaning.

2.4.4. Snow

Because snow clean-up effectiveness is necessary in major cities in North America for the functioning of the city following frequent large snow fall, it was used here to present management strategies that can be applied to disaster sediment clean-up.

For snow to form, it requires a temperature below water freezing temperature (0 degrees Celsius) and the presence of moisture (NSIDC, 2013). For snow to accumulate on the ground, the ground temperature needs to be at least 5 degrees Celsius (NSIDC). The weather condition during the snow fall will affect its characteristic on the ground:

- Small flake will compact more than large flake,

- Strong wind may break down the snow crystals into smaller fragment,
- Time will modify the snow conditions such as melting (increasing water content), freezing and compaction.

Snow clean-up is only required in some regions of the world. In some cases, snow can be placed on the side of the road to meld, but in large urban area in the North America, such as Montreal, a large amount of snow can exceed the potential for road stock pile and required a more complex clean-up (NSIDC, 2013). In regions not accustomed to snow fall, it can have devastating impacts such as the snow fall over Canterbury on the 8th of July 1992 which up to 1m of snow accumulation occurred over several days and forced roads to close, power lines were brought down and tens of thousands of cattle and sheep were trapped (Brenstrum, 1998).

2.4.4.1. Snow Removal in Montreal

The city of Montreal is one of the major economic center of Canada, it has a population of 1.64 million people and is affected by approximately 255 cm of snow per winter (Montreal City website). Montreal's expertise in snow removal was used by Beijing city in 2011 to learn and upgrade their practice in the domain (Montreal City website, Operation Snow Removal, communiqués). A fast and effective removal of snow is necessary to allow the continuous operations throughout the city (Figure 4). Thus, Montreal was used to demonstrate the strategies behind these operations and how they can be related to other fine sediment removal (Campbell and Langevin (1994), Perrier et al. (2006)). Snow removal is divided into four major operations presented in Table 7.

The principal strategy behind the clearing in Montreal is to clean-up the main arteries first to get the traffic moving. The city is divided into main sectors to allow a more effective clean up due to different amount of snow and traffic. In order to minimise transport, the public is made aware in advance when the snow blowers will collect the snow. Modelling is used to develop the best sector division and identify routes to minimise transport and increase efficiency. This type of modelling could be challenging to use for earthquake induced liquefaction because it is hard to estimate the level and location of roads damage; liquefaction does not only add a layer of fine grained deposit over the ground such as snow or tephra fall but it also deforms it so that roads need repair and clearing.

FIGURE 4: SNOW REMOVAL ALONG A HIGHWAY IN MONTREAL (CANADA) BY CONTRACTORS PHOTO CREDIT: ALLEN MCINNIS, MONTREAL GAZETTE

TABLE 7: SNOW REMOVAL MAJOR OPERATIONS AND POSSIBLE APPLICATION

Operation	Application
Spreading of de-icers and abrasives	Ice/Snow specific
Clearing	Any fine grained sediment *
Loading	Any fine grained sediment *
Disposal	Any fine grained sediment *

* such as snow, tephra, liquefaction

2.5. Fine Grained Sediment Clean-up Summary

An operational transport network is vital in a disaster response situation for rescue and emergency services restoration. The removal of unconsolidated fine grained sediment following in normal environment and in a disaster can be complex, time consuming and expensive (Brinkmann and Tobin 2001, USGSa, 2010, Villemure *et al.*, 2012).

Spontaneous volunteerism can overflow the affected community, if it exceeds the actual need or if it is not necessary (Auf der Heide, 1989). The importance of communicating the actual needs to emergency management organisations is therefore primordial to avoid this surplus that can impede and complicate disaster response. They are also recognised to bring positive outcomes if well managed.

In spite of their different origin and deposition processes, disaster fine grained sediment has the potential to impact lifelines and will require clean-up. Table 8 present a summary of past event clean-up volume, costs and time of various disaster sources.

Past events have provided an opportunity to investigate the logistics, volumes, time and financial costs to conduct a massive urban clean-up and presented a valuable case study to support the importance of planning for urban clean-up following fine grained and unconsolidated depositions following a disaster such as volcanic eruptions or earthquakes.

TABLE 8: FINE GRAINED SEDIMENT CLEAN-UP COMPARISON

CASE STUDY	2004 TSUNAMI Sri Lanka (Brown et al. 2011)	PACAYA (Wardman et al. (2012)	TONGARIRO TEPHRA FALL (2012)
VOLUME	500 000 tonnes	11,300,000 m^3	Small (104m^3)
COST ($US)	5-6 million	0.2 million (just for heavy machinery)	Total ~ 8,000 Direct clean-up ~ 5,000, Secondary clean-up ~ 3,000.
TIME	N/A	3 weeks	4 days

Chapter 3. Liquefaction Clean-up in Christchurch: Qualitative Study

3.1. Introduction

Investigating the management, logistics, resources, volumes, time and financial costs needed to conduct a large-scale clean-up operation in urban areas following a disaster was a primary goal of this research.

This chapter presents the experience of cleaning-up liquefaction ejecta in Christchurch city during the Canterbury earthquake sequence in New Zealand's central South Island (2010-2011). It investigates the logistics, resources and financial costs that were required to conduct a large-scale fine grained sediment (<1 mm) clean-up operation in an urban areas. The Christchurch city liquefaction ejecta clean-up is a valuable case study to support the importance of planning for urban clean-up following fine grained and unconsolidated depositions by a disaster.

The result from this section has been presented at the 2012 NZSEE Conference as a paper and a poster. The interviews were conducted in a group of three students but the interpretation of the results and the writing of the paper credits are of the thesis author.

3.2. Method

A series of semi-structured interviews were held with organisations (Christchurch City Council, Fulton-Hogan Ltd, City Care Ltd) and two main volunteer groups ('*Farmy-Army*' – a group organized by rural organizations and made up mainly of farmers and rural workers; and the '*Student-Army*' – a group organized by the University of Canterbury Student Association and made up mainly of tertiary students at first but anyone was welcome to join) involved in the clean-up and management of liquefaction ejecta from Christchurch. A list of questions was prepared based on review of disaster waste literature and framed in the Christchurch context. They focused on costs breakdown, time, volume, resources, coordination, planning and priorities. Interviews were conducted face to face, by email or by phone and included guided visit to Burwood landfill, the main liquefaction disposal site. The interviews were supported with review of relevant literature and media reports. Example of the survey questions are presented in Appendix E.

3.3. Canterbury Earthquake Sequence: Since 4 Sept 2010

3.3.1. Tectonic Setting

New Zealand is located on a convergent plate boundary where the Australian and the Pacific plates move obliquely relative to each other (Walcott, 1998) resulting in a regional oblique convergence movement of 37 mm/yr (Figure 5). This movement is mostly accounted by the Alpine Fault (70-75 %) and the Marlborough Fault zone (Howard *et al.* 2005), but it is also transferred to the surrounding region such as the Canterbury plains. These faults present a significant and poorly understood hazard that requires further research (Pettinga *et al.* 2001). New Zealand is still geologically active and is the sites of large historical earthquakes such as the Mw 7.8 Hawke's Bay (1931), Mw 6.5 Edgecumbe (1987) and Mw 7.8 Dusky Sound (2009).

3.3.2. Overview of the Canterbury Sequence

On 4 September 2010, the Mw7.1 Darfield earthquake occurred along the previously unknown Greendale Fault. It produced a ≥28 km long surface rupture with an E-W trending through low relief farmland 40 km west of Christchurch, leading to widespread damage and disruption (Quigley *et al.*, 2012). Since then, a large number of aftershocks with strike-slip and reverse faulting components have continued to affect the central Canterbury and Christchurch region. Significantly, the aftershock pattern has moved progressively eastward towards and beyond the Christchurch urban area (Figure 5, Figure 6). These earthquakes include the Mw6.2 Christchurch earthquake on 22 February 2011 (which lead to 185 deaths and widespread damage throughout Christchurch city), Mw6.0 on 13 June 2011 and Mw6.0 earthquake on 23 December 2011 (although the December event clean-up is not considered in this research). As of 30 June 2013, the ongoing sequence counts over 13,400 recorded earthquakes, with over 60 larger or equal than Mw 5 (GeoNet, 2013). The nomenclature used to refer to the earthquakes in the following study is presented in Table 9.

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Each of the four major earthquakes induced significant ground-shaking in Christchurch area and resulted in widespread liquefaction, particularly in the eastern suburbs of Christchurch (Bradley & Cubrinovski, 2011). Graph of aftershock < Mw5 (Figure 6) identify the aftershock events that created enough liquefaction ejecta to necessitate a large deployment of resources (22 February 2011, 13 June 2011).

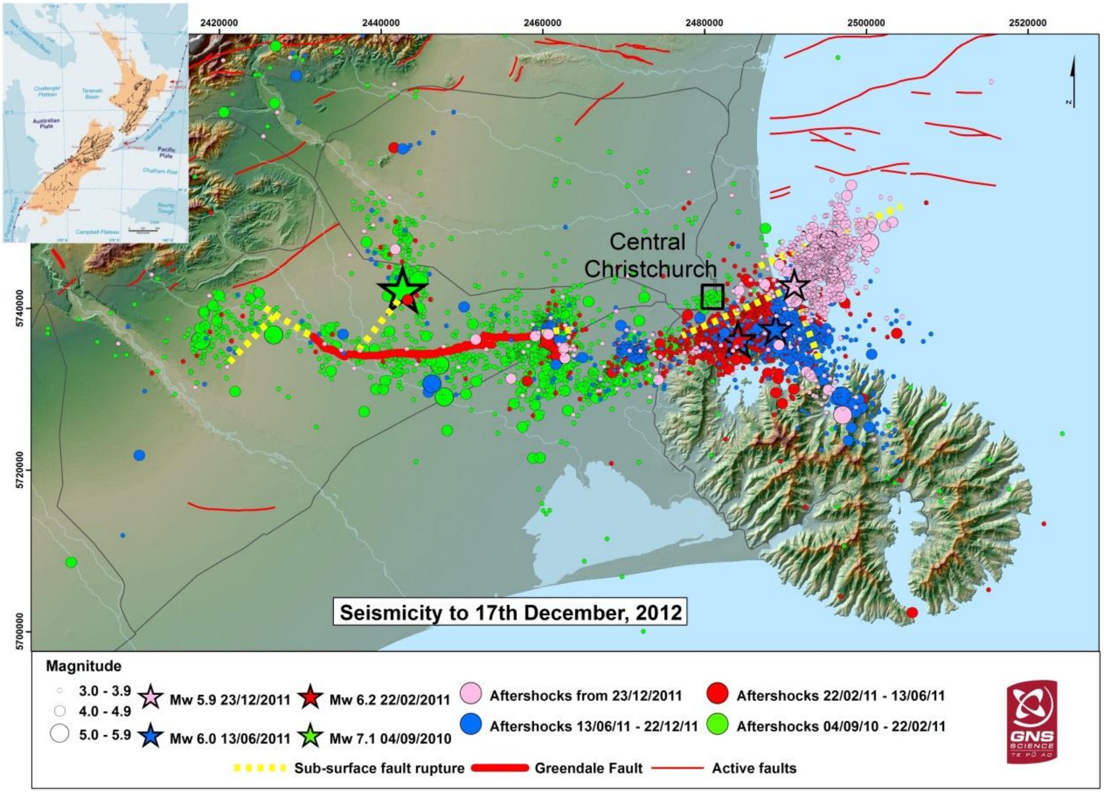


FIGURE 5: GENERAL TECTONIC OF NEW ZEALAND AND MAP OF THE CANTERBURY AFTERSHOCK SEQUENCE. SOURCE: GNS, 2013)

TABLE 9: EARTHQUAKE RELATED NOMENCLATURE USED IN THIS STUDY

Earthquake	Date	Nomenclature	Associated clean-up time period
Mw7.1 Darfield earthquake	4 September 2010	Darfield	4 September 2010 – 21 February 2011
Mw6.2 Christchurch earthquake	22 February 2011	Christchurch 1	22 February 2011 – 12 June 2011
Mw6.0 Christchurch earthquake	13 June 2011	Christchurch 2	13 June 2011 – 22 December 2011

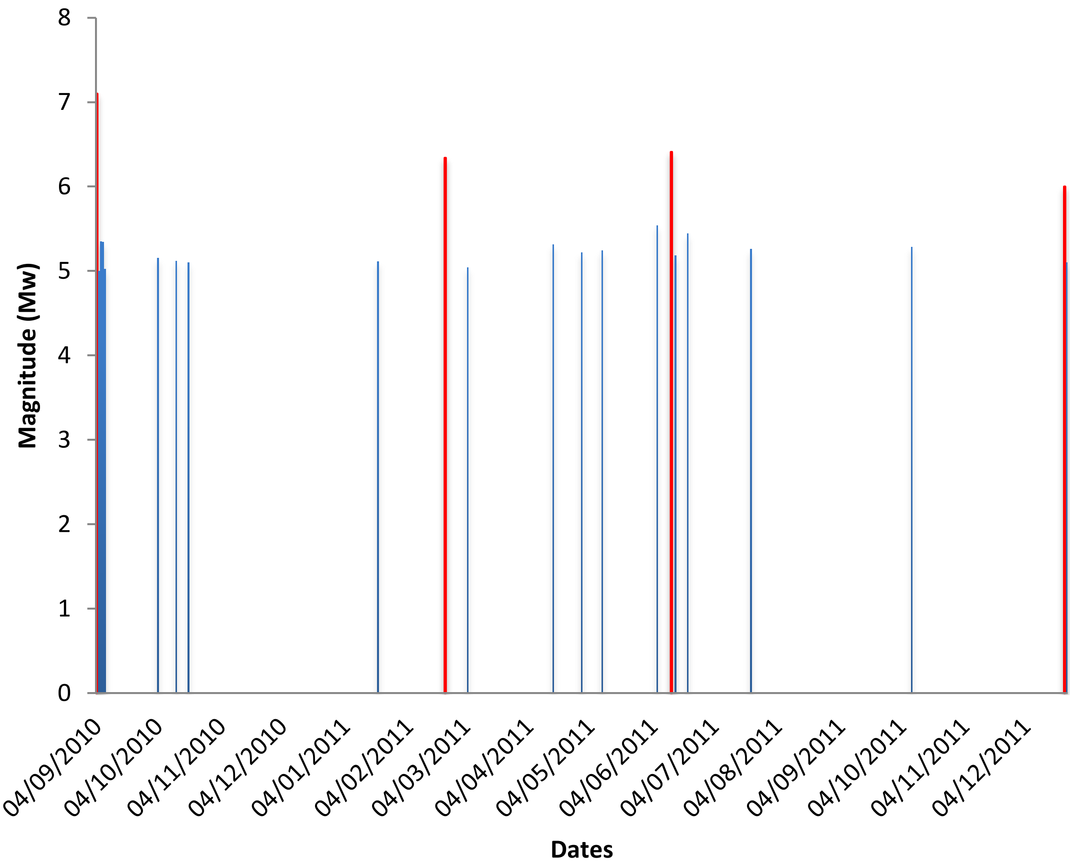


FIGURE 6: EARTHQUAKES > MW5 FOR THE PERIOD OF 4 SEPTEMBER 2010 TO DECEMBER 2011

3.4. Liquefaction Ejecta

3.4.1. Liquefaction Ejecta Impacts

The risk of earthquake induced liquefaction occurring in Canterbury was previously identified from various studies (Ecan 2011,Environment Canterbury 2011, Christenson 2001, Stirling et al 1999, Anderson & McMorran 2003) and from past earthquake events like the 1901 Cheviot Earthquake (Christensen 2001). Plus, it was well established that much of eastern and central Christchurch was constructed on soils which would likely liquefy during strong ground shaking (CELG 1997). However, the volume, scale and recurrence of liquefaction ejection across the city were a surprise and showed that the risk had been underestimated.

The liquefaction ejecta created unique impacts to Christchurch city. In each event, road networks were badly affected by liquefaction induced ground deformation which created features such as domes, cracks, holes, lateral spreading, differential settlement, ejection of fine grained sediments (<1 mm) at the surface and ponding/pooling water. Roads in the eastern parts of the city were difficult to transit or sometimes impassable for two-wheel drive traffic. The poor state of roads contributed to significant traffic congestion on major arterial roads, the central business district closure and significant internal population migration within and out of the city. The poor access and congestion would have affected the initial speed of the clean-up operations after each liquefaction event. This problem was reflected at the Burwood disposal site where low numbers of trucks were seen in the first few days (Harris pers comm., 2011).

Unmanaged liquefaction ejecta also caused damage to urban infrastructure. The ejecta continually eroded over time, creating a sediment source which could infiltrate and contaminate the damaged storm water system and the urban waterways. From a human health point of view, the liquefaction ejecta posed several hazards. Due to the extensive damage to the sewage disposal networks from lateral spreading and differential settlement, there was the risk that much of the liquefaction ejecta had been contaminated with raw sewage creating a long-term health risk to the population (McDonald pers comm., 2011). During hot and windy conditions, the dry finer portions of ejecta was mobilised by the wind creating a possible respiratory health hazard. Following the February earthquake the Ministry of Health suggested that personal protection such as gloves, gumboots and masks should always be worn when dealing with liquefaction ejecta.

With thousands of residential properties inundated with liquefaction ejecta, residents were eager to remove it from their properties to restore household functionality, remove the depressing grey deposits and retain a sense of control and normality. However, with hundreds of thousands of tonnes of sediment to clean, many residents lacked the capacity (time or resources) to clean-up their properties without external assistance.

3.4.2. Liquefaction Ejecta Clean-up

The liquefaction ejecta clean-up response was co-coordinated by the Christchurch City Council (CCC). Ejecta removal from private property was primarily carried out by private property owners and volunteers using hand tools and some small earthmoving plant. Ejecta collection from public areas (including ejecta moved from private property to kerbside) was executed by a network of road maintenance contractors (including Fulton-Hogan Ltd and City Care Ltd) who were required under the emergency section of their maintenance contracts to respond and supply plant and personal as required. In addition, sewage and stormwater network maintenance contractors had to hire specialist ejecta and sewage "sucker" trucks to clear blocked stormwater and sewage pipes.

The city was generally separated between the two major road contractors; *City Care* and *Fulton & Hogan*. City Care was in charge of the Northern smaller zone (Papanui) (Scott pers comm., 2012), and *Fulton & Hogan* was in charge of a larger section including the south and the eastern suburbs. Figure 7presents a simplified partition of the city that can be compared with the land damage liquefaction map (Figure 9) to identify that Fulton and Hogan were in charge of a larger portion of the most affected areas. The contractors work was primarily located within their respective zones but there was some overlying clean-up work in some highly affected zones.

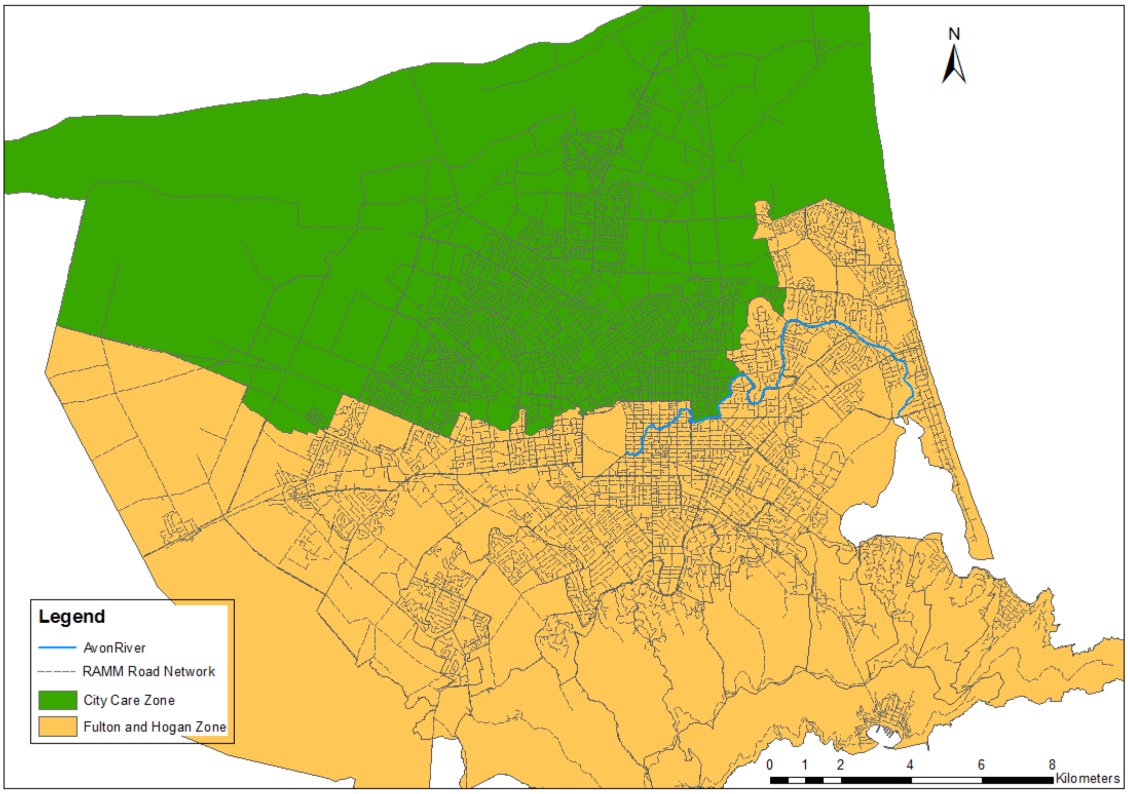


FIGURE 7: SIMPLIFIED REPRESENTATION OF FULTON & HOGAN AND CITY CARE RESPECTIVE CLEAN-UP ZONES

The first occurrence of liquefaction ejecta on 4 Sept 2010 was less voluminous than in the Christchurch 1 and Christchurch 2 2011 earthquakes and proved to be a valuable learning experience (McDonald; Hautler pers comm., 2011). Clean-up strategies developed in Darfield, such as definition of clean-up zones, prioritizations and methods, equipment/resources and connections provided a strong foundation that evolved during subsequent events (McDonald; Chapman; Rutherford pers comm., 2011). The general strategy for ejecta clean-up identified through the interviews is presented in Figure 8. Public safety and safety of the working crews were a major concern throughout the clean-up for clean-up management teams (McDonald; Hautler pers comm., 2011, Mulder, 2012). For example, the welfare of the staff was controlled by managing their working hours and making sure they were having time off work and appropriate support (Mulder, 2012, Lucas pers comm., 2012). The amount of time per volume of collected sediment decreased as the chosen method, communication and coordination between the involved parties improved.

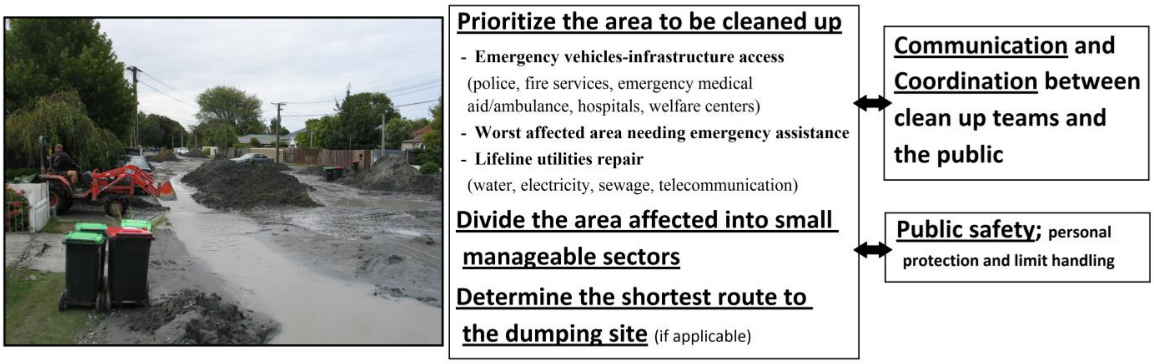


FIGURE 8: GENERAL STRATEGY FOR CHRISTCHURCH LIQUEFACTION CLEAN-UP. PHOTO: PILES OF LIQUEFACTION EJECTA CLEANED FROM RESIDENTIAL PROPERTIES AND ROADS, READY FOR REMOVAL BY HEAVY EARTH MOVING MACHINERY AT BRACKEN STREET IN THE SUBURB OF AVONSIDE FOLLOWING THE CHRISTCHURCH 1 EVENT. (PHOTO CREDIT: JARG PETTINGA)

The optimal liquefaction clean-up process was found to include the following five steps (McDonald pers comm., 2011, Scott pers comm., 2012):

1) Contractor undertakes an initial inspection, defines small working zones on the basis of volume of sediment and local conditions, and identifies priority zones (Figure 9).
2) Contractor undertakes an initial ejecta removal from the street and pathways to facilitate transport - typically using heavy earth moving machinery (Figure 10).
3) Contractors, volunteers and property owners/residents remove ejecta by hand (i.e. shovel and wheelbarrow) from difficult to reach areas that machinery cannot reach, including private properties, areas around vehicles, gardens, driveways and schools (Figure 11). Material is accumulated in the street away from the curb (for easy pick up by diggers or loaders) and away from drains (to avoid sediment ingestion into waste water networks).
4) Ejecta is collected by contractors with machinery and either a) transported to disposal site at Burwood Resource Recovery Park (former city landfill) or b) stored in a temporary strategic location, prior to transport to disposal site.
5) Final cleaning via water-carts (truck mounted water tank and sprinkler system) to suppress windblown ejecta from the roads and to clean the ejecta possibly left into the storm water system (Figure 12).

*This general method would be varied according to severity of sedimentation and access to available resources.

*Based on Christchurch experience and other fine grained sediment (<1 mm) clean-ups such as volcanic tephra (Johnston et al. 2001).

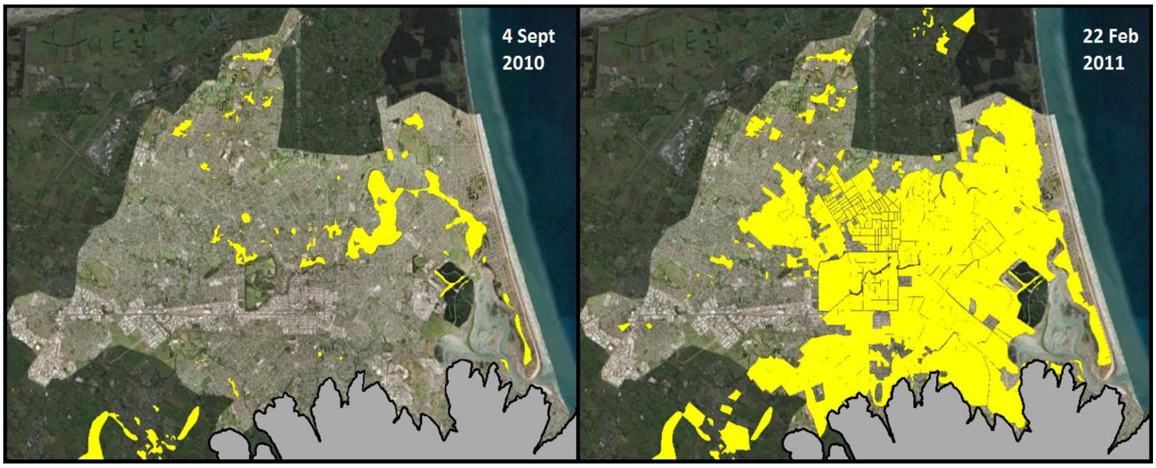


FIGURE 9: "OBSERVED LIQUEFACTION OVERVIEW MAP" IN CHRISTCHURCH FOR THE 4 SEPTEMBER 2010 AND 22 FEBRUARY 2011. YELLOW AREA SHOW OBSERVED LIQUEFACTION. SOURCE: EQC AND TONKIN AND TAYLOR LTD.

FIGURE 10: QUAKE DAMAGED SINCLAIR ST, POST 23.12.11. PHOTO CREDIT: MARK JS ESSLEMONT, WOZA WANDERER BLOG, 2011

FIGURE 11: STUDENT VOLUNTEER ARMY HELPING WITH THE EARTHQUAKE CLEAN-UP. PHOTO CREDIT: UNIVERSITY OF CANTERBURY EVE WELCH

FIGURE 12: CONTRACTORS SPRINKLING THE QUAKE DAMAGED SINCLAIR ST. AND RAWSON ST. (PHOTO CREDIT: MARK JS ESSLEMONT, WOZA WANDERER BLOG, 2011)

3.4.3. Liquefaction Ejecta Disposal

Due to the contaminated state of some deposits and the extremely large volumes (> 500,000 tonnes), it was necessary to store the collected sediment outside of the city for storage and secure decontamination. The majority of liquefaction ejecta were disposed of at the Burwood Landfill (also known as the Burwood Resource Recovery Park) in Bottle Lake Forest following each earthquake (Figure 13). The Burwood landfill had been operational from 1984-2005 serving Christchurch's solid waste disposal needs and at the time of the earthquake was undergoing a final stages of restoration and remediation work (started in 2010). The site had been identified as a storage area for solid disaster waste during disaster resilience planning in the 1990's and 2000's due to its proximity to the city (~10 km) and presence of a natural fine-grained barrier between the landfill and the shallowest aquifer that protects local groundwater resources (Harris pers comm., 2011).

The severity of road damage following the February quake and the huge volumes of ejecta led to stock piles being created in strategic locations in the city before being transported to Burwood (Figure 14) (Harris; Hautler pers comm. 2011, Scott pers comm. 2012). The contractors were using staging area such as breeze road, because it was hard for the trucks to move during the day, they were doing most of the transport between the staging area and Burwood during the night (Lucas pers comm. 2012). One of the principal staging area was the breeze road site. To facilitate movement, most of the transports from the staging areas to Burwook landfill were conducted during the night (Lucas pers comm., 2013). In addition, small quantities were disposed of by Fulton Hogan at their quarry in Pound Road due to proximity (Haulter pers comm. 2011). Future uses for liquefaction ejecta have been suggested for construction of concrete blocks or bricks, and engineering fill for levelling ground for sports fields and parks, however, to date the final uses have not been determined.

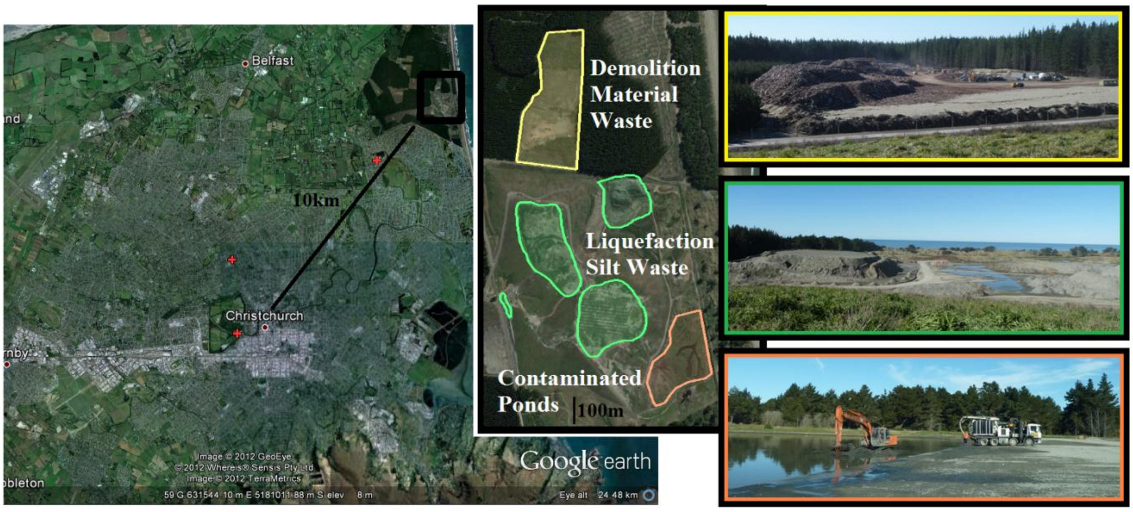


FIGURE 13: BRUWOOD RESOURCE RECOVERY PARK LOCATION TO CHRISTCHURCH CENTRE AND SIMPLIFIED MAP OF STAGING AREAS FOR DIFFERENT TYPE OF WASTE. PHOTO: STAGING AREAS ON 25 AUGUST 2011.

3.4.4. Coordination and Communication

The liquefaction clean-up operation involved many different organisations and its effectiveness relied on extensive and well managed coordination and communication. During peak clean-up after the 22 February 2011 earthquake, over 2000 contractors were working on the clean-up along with approximately 1000-2000 *Student-Army* and *Farmy-Army* volunteers per day (Hautler; Fulton; Rutherford; Chapman pers comm. 2011, Scott pers comm. 2012). During this period, the Burwood landfill was accepting one truck every 20 seconds into the waste disposal area (Harris pers comm. 2011). Table 10 present the workforce distribution from Fulton & Hogan throughout the Christchurch earthquake sequence clean-up.

TABLE 10: WORKFORCE DISTRIBUTION

Events	Fulton & Hogan workforce
September 4th 2010 – magnitude Mw 7.1	255
February 22nd 2011 – magnitude Mw 6.3	1500 (including volunteers) 415 (staff and substitute)
June 13th 2011 – magnitude Mw 5.6, magnitude Mw 6.3	498
December 23rd 2011 – magnitude Mw 5.8, magnitude Mw 5.3	130
Total	2383 with volunteers 1298

Clean-up managers noted the importance of a clear strategy which was underpinned at all times by clear and concise communication and coordination between council, contractors, volunteers, the public and other stakeholders, such as Civil Defence and other lifeline organisations who might require access to specific sites (e.g. for repairs). Initially communication between groups was poor, leading to confusion and double handling (McDonald; Russell; Chapman; Rutherford pers comm. 2011). For example, information such as where to dispose of cleared ejecta was not transmitted to volunteer groups, leading to stock piles at inappropriate locations (e.g. private car parks) (Figure 14).

All organisations stated that local knowledge, trust, contacts and existing informal relationships significantly enhanced the effectiveness of the clean-up management. In fact, the contacts and relationship established between different agencies involved and lessons from the first clean-up following the Darfield 2010 earthquake made the mobilisation a lot more effective in the following events (Hautler; Rutherford pers comm. 2011).

FIGURE 14: LEFT: AERIAL PHOTO 655 BREEZES ROAD BEXLEY, SHOWING TEMPORARY STORAGE AREA FOR LIQUEFACTION EJECTA 25/02/11 (SOURCE: KOORDINATES 2011); RIGHT: ESTIMATED >500,000 TONNES OF LIQUEFACTION EJECTA REMOVED FROM THE CHRISTCHURCH URBAN AREA AFTER THE 22 FEBRUARY

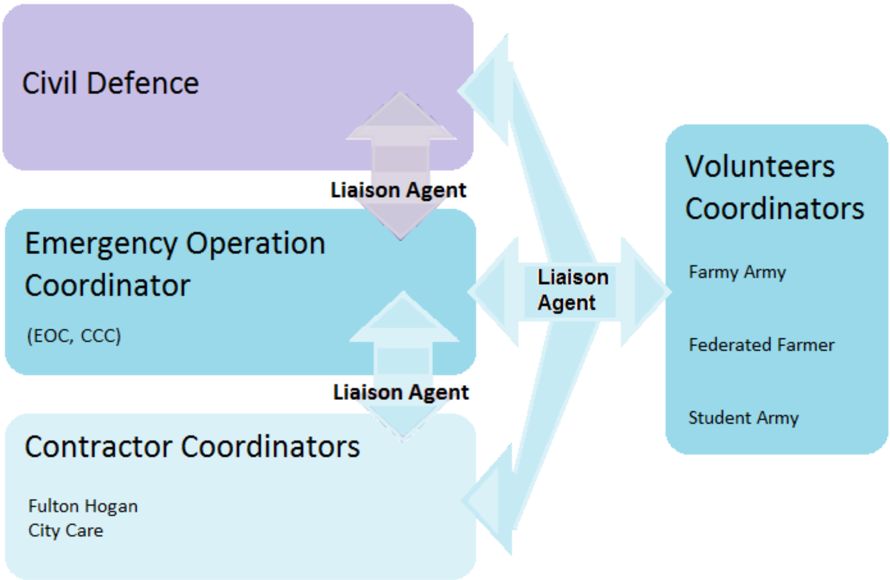
The large number of volunteers and the different level of skills and resources available between each of the groups involved in the clean-up operations made for challenges. Ensuring coordination of groups to limit multiple clean-ups of the same road in sequence with contractors took significant planning, but ultimately proved a powerful partnership. Initially, clean-up managers were concerned about health and safety amongst the volunteers, particularly in terms of operating around heavy machinery and access to sufficient food and water. However, this was remedied through briefings and strong leadership in each of the volunteer organisations. Coordination was further significantly enhanced when a job dispatch and mobile workforce management system, GeoOp system, was offered to the *Student-Army* with no usage cost. It was successfully used to coordinate the work of volunteers around the city (GeoOp 2012, Rutherford 2011).

3.4.4.1. Coordinated Incident Management System (CIMS)

The use of an incident management system (IMS) and staff trained in its use was essential for managing the clean-up (McDonald pers comm. 2011). New Zealand Civil Defence and Emergency Management (CDEM) uses the Coordinated Incident Management System (CIMS) which provides a unified, scalable and integrated system designed to enhance and empower on-site incident managers and communication. It is based on distributed accountability, which puts the people closest to the incident in charge and responsible in order to facilitate decision making and accelerating response time. Clean-up organisations reported there were significant benefits from having a common IMS structure in place, which was familiar from previous CDEM exercises in addition to snow and flood clean-up operations (Figure 15). Some challenges were encountered when national CDEM began to relieve local CDEM, adding “unnecessary complications and poor situational awareness”.

CIMS was used effectively to communicate between the different clean-up organisations and with the public. The uniformity and control of the information was essential to avoid misunderstandings. The CIMS structure created one unique source of information for: road closure and opening, evolution of clean-up, identifying what had been done and what still had to be done. This information was available on a unique website where everybody would get the same and the most up to date information (McDonald pers comm. 2011).

FIGURE 15: EMERGENCY CLEAN-UP CHAIN OF COMMAND FROM CHRISTCHURCH LIQUEFACTION CLEAN-UP



3.4.4.2. Volunteer Management

It is well established in disaster literature that volunteers can have a significant positive impact on disaster victims by reducing stress, assisting in recovery activities and providing guidance throughout healing process (Fernandez *et al.* 2006). However, spontaneous volunteerism also represents a management problem for emergency management organisations not prepared to receive them, which can lead to major ineffectiveness of the response operations. This occurred during the early days of the Christchurch clean-up operations, as the voluntary force from the *Student Army*, the *Farmy Army* and others were slowed down at first due to lack of preparedness (McDonald; Rutherford 2011). A team of project managers was rapidly put in place to co-ordinate all the efforts. The principal volunteer teams evolved from two independent forces (*Farmy Army* and *Student Army*) in February 2011, with limited communication between them, to a joined organisation under the *Farmy Army* to work as a single body in June (Chapman pers comm. 2011). The joint effort and sharing of information was recognised to have great potential (Rutherford pers comm. 2011). The volunteer set-up could have been more rapid and efficient if there had been better provisions for managing volunteers in CDEM plans (Russell pers comm., 2011).

The *Farmy-Army* formed after the February 2011 event and was active again in the Christchurch 2 2011 event. They contributed 10-14 days of voluntary work after the February quake with thousands of workers and around five days volunteered for the Christchurch 2 clean-up effort, partially because of the smaller scale and a sense of volunteer fatigue (Chapman pers comm. 2011). A significant contribution was made by the *Farmy-Army* with the use of equipment including tractors, trucks and human resources.

The total volunteer resources from *Student-Army* were difficult to ascertain due to the transient nature of the volunteer effort. Over 10,000 people had already joined their *Facebook* group *Student Volunteer Army* on the 24 February 2011 (One News 2011) and thousands of *Student-Army* volunteers are thought to have worked an estimated 75,000 hours (Webster pers comm. 2011). It was calculated that they offered over $NZ 1 million worth of labour only during the first week after the February quake and help went on until the 20th of March (Rutherford pers comm. 2011). The Internet, social media and the coordination system GeoOp, were powerful tools for the *Student-Army*. The Social Network *Facebook* was used by Student Volunteer army in Christchurch and has proven to be of great use to communicate needs with the public and avoid misleading communication to the outsider. Responses were rapid and very generous from local to international business and individuals (Rutherford pers comm. 2011). Actual time communication on the page could let the public know their needs and also if their needs had been filled or who would take care of it. For some disaster access to technology will not be possible and other more basic way of communicating will have to be considered.

In conclusion, convergence, the need to help and spontaneous volunteerism are not new to the Christchurch earthquake sequence. They have been observed throughout history and will be seen in future disaster as well. Coordination, communication and management issues associated with spontaneous volunteer are recurrent throughout studies (Fernandez *et al.*, 2006). Recent studies have shown that helping during a disaster has a great positive impact on the affected community as well as on the helpers. The value of volunteerism during a disaster is hard to calculate, but it saves money and time, it bring hope and good feeling to the population and it can free up more qualified person from basic work so they could be useful in the process.

3.5. Duration and Estimated Cost of the Clean-up

Despite the volume of liquefaction ejecta being significantly different for each event (Table 11, Figure 16), the duration of clean-up time was approximately two months following each event with most of it being completed during an intense period of cleaning lasting two to three weeks after each event. Interviewees indicated this reflected an ability of contractors and volunteer groups to scale their response to the need required. Table 11 shows the estimated liquefaction ejecta volumes and time to remove the materials.

TABLE 11: ESTIMATED MASS OF EJECTA REMOVED IN CHRISTCHURCH BETWEEN SEPTEMBER 2010 AND AUGUST 2011

Events	Tonnes of ejecta removed		
	Fulton Hogan	City Care	Total
September 4th 2010 - magnitude 7.1	31,000	20,000	51,000
February 22nd 2011 – magnitude 6.3	315,655	81, 370	397,025
June 13th 2011 – magnitude 5.6, magnitude 6.3	85,390	No information	85,390
December 23rd 2011 – magnitude 5.8, magnitude 5.3	32,500	No Information	32,500
Total	**464,545**	**101,370**	**565,915**

During the period of qualitative data collection, the final financial cost of the clean-up effort of the contractors was not available. However, from available interview sources the estimated cost of clean-up at March 2012 was approximately $NZ 30,000,000.00 (Table 12). The interview data did not offer sufficient information to identify the resources, costs and time required to perform a widespread fine grained sediment (<1 mm) clean-up in an urban environment. Interviewees suggested analysis of data collected by contractors during the Christchurch liquefaction ejecta clean-up, managed by the Christchurch City Council road asset management system (RAMM) would be required. A review of the costs of Christchurch liquefaction clean-up following the RAMM data analysis is presented Chapter 4.

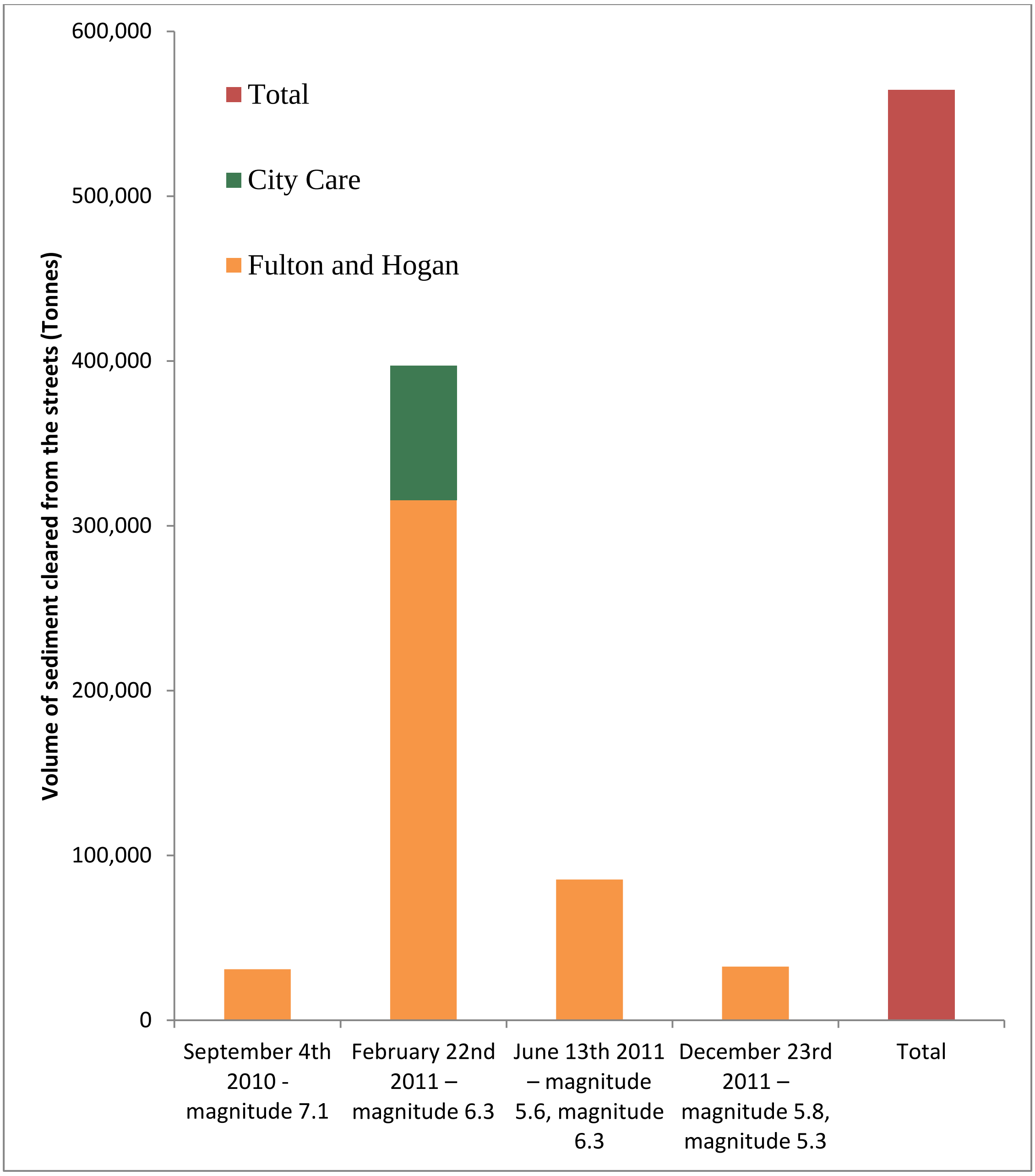


Figure 16: Estimated Clean-Up Volumes

TABLE 12: ESTIMATED COSTS FROM THE QUALITATIVE STUDY OF LIQUEFACTION CLEAN UP FOLLOWING THE 4 SEPT 2010, 22 FEB AND 13 JUNE 2011 EARTHQUAKES IN CHRISTCHURCH.

Items	**Estimated costs ($NZ)**	
	Subtotal	Total
Transportation Costs for calculation	550,000 tonnes of ejecta at an average of $0,28/km/tonne ($5.50/T)*	$ 3,036,000.00
Disposal Site Infrastructure		$ 800,000.00
Disposal Site Running Costs	$500,000 *(est. post 4 Sept 2010)* $1,200,000 *(1 month post 22 Feb 2011)* $500,000 *(est. post 13 June 2011)*	$ 2,200,000.00
Disposal Cost	550,000 tonnes of ejecta at 5$ per tonne	$ 2,750,000.00
Contractor Staff Time Contractor Operation Cost	$2,000,000 Fulton Hogan $15,000,000 City Care (surface clean-up of the northern city area)	$ 17,000,000.00
Estimated Volunteers Labour Contribution	$1,000,000 (Student Army) $1,000,000 (Farmy Army)	$ 2,000,000.00
Donation to the Student Army	$20,000 MSD $10,000 Mitre 10/ANZ: wheelbarrows $30,000 (other)	$ 60,000.00
Total estimated costs		**$NZ 27,846,000.00**

*Based on Johnston et al. 2001

* based on (McDonald; Harris; Rutherford pers comm. 2011, Scott pers comm. 2012)

3.6. Summary

The prompt removal of liquefaction ejecta after an earthquake is essential to restore affected lifelines utilities, facilitate transportation and relieve the stress and disruption within affected communities. However, it is complex, time consuming and expensive, representing a major social, economical and even political challenge for the clean-up management team. Lessons from the Christchurch liquefaction clean-up experience agree with guidance from Brown et al. (2011) who note that key element to success include good public communication and public consultation during the disaster waste management process. Both elements can increase public understanding of the necessity for emergency measures, and also increase the authorities' appreciation of publically unacceptable options.

There were a number of similarities to other fine sediment clean-ups (particularly volcanic tephra fall) observed during the Christchurch liquefaction ejecta clean-up experience:

- Widespread and thick deposition of fine grained sediment in or on a city requires municipal assistance and coordination.
- Emergency planning and the use of the CIMS system during the emergency were important to facilitate a rapid recovery from the liquefaction hazard.
    - Rapid identification of a disposal site is crucial. Significant benefits were realised in Christchurch by having a pre-selected site close to the city.
- Fine sediment is very difficult to handle when saturated (non-cohesive and heavy) or dry (hardens and is susceptible to erosion by wind). Fine sediment is ideally collected when slightly moisten.

Observations unique, but not necessarily exclusive to the Christchurch experience includes:

- Management of volunteer groups during clean-up operations can be extremely challenging, resource intensive and require their rapid adaption and integration into the incident management system. However, their contribution is invaluable and greatly adds to clean-up effectiveness. There are also a number of social benefits, including community spirit.

- Management of liquefaction ejecta, generally took around two months, despite variable extent and volume of ejecta,
- The financial cost of clean-up is in the order of multiple millions of dollars.
- Light and heavy earth moving machinery is essential for the large scale removal of deposits. However, this is most effective when properly integrated and coordinated with ground teams who clean hard to reach areas.
- Clear communication and coordination between clean-up command and the general public (affected property owners and volunteers) is essential for achieving the most efficient and effective clean-up.

The liquefaction clean-up experience in Christchurch following the 2010-2011 earthquake sequence has emerged as a valuable case study to support further analysis and research on the management, logistics and costs not only for liquefaction related phenomena, but also any kind of hazard which might cause the deposit of large volumes of fine grained sediment in urban areas, (e.g. volcanic tephra or flooding; see Johnston *et al.* 2001).

Chapter 4. Christchurch Liquefaction Ejecta Clean-up: Quantitative Study

4.1. Introduction

The goal of this chapter is to quantify the resources, time and cost required for general fine grained sediment (<1 mm) clean-up in urban environments following a disaster based on the Christchurch liquefaction ejecta clean-up. The quantification of this event is important because large fine-grained sediment clean-up have rarely been documented in a quantifying manner. Debris clean-up following a disaster has proven to be a large portion of the disaster recovery cost, for example, 27% of the recovery cost in the US for disasters between 2002-2007 was attributed to debris removal (FEMA, 2007 from Brown *et al.*, 2011). Observing how the city of Christchurch reacted and evolved with time helped identify lessons that can be used in the planning or preparedness section of the emergency management phase. This analysis follows on from the qualitative study of the clean-up of Christchurch liquefaction ejecta presented in Chapter 3 and with the aim of better completing the analysis of the Christchurch case study.

This chapter summarizes the resources, cost, activities and time required for the Christchurch clean-up based on Christchurch City contractors database and describes the method used to analyse it. The results illustrate and compare the city clean-up following each of the three major liquefaction ejecta events. It presents a quantitative and comparative perspective of the available clean-up data with the goal to discover valuable trends and insights that can be applied to other fine grained sediment (<1 mm) clean-up impacting urban environments. The results from this quantitative analysis are compared to the interview process and present a social-scientific-economic perspective of an urban clean-up.

4.1.1. Introduction to RAMM

In order to quantify the clean-up of the roads following the three majors widespread liquefaction event in Christchurch (4 September 2010, 22 February and 13 March 2011), a quantitative analysis was carried out using the *RAMM (Road Assessment and Maintenance Management)* database of Fulton & Hogan Ltd. (*Fulton & Hogan*). This analysis was completed following on from the interview process presented in Chapter 3.

RAMM is a common database used by Christchurch City Council (*CCC*) for tracking and charging road maintenance city contracts. It provides a common operating system for contractors, such as *Fulton & Hogan* and City Care Ltd. (*City Care*) to keep work records. It is intended to support regular road maintenance work and had to be modified to support earthquake related work.

During the liquefaction clean-up following each earthquake, RAMM was used to coordinate and manage clean-up activities and to track costs. Only Fulton & Hogan Ltd. provided permission to use their dataset from RAMM. Fortunately for this study, they were responsible for the largest area of the city including the most heavily affected suburbs (Figure 7 and T&T maps).

The data available to us covered only the 3 first major liquefaction ejecta events (4 September 2010 (Darfield), 22 February 2011 (Christchurch 1) and 13 June 2011 (Christchurch 2)). Data ranges from 4 September 2010 to 5 December 2011 and covers at least 16 weeks following each event. From the RAMM dataset, it is possible to locate jobs with cost, hours and resources attributed to it and study the temporal and spatial evolution of the clean-up.

This information is important because if compared for each event, patterns such as minimum and maximum time of clean-up for any soft sediment event or trend to anticipate the cost of clean-up may be identified.

4.1.2. Data Entry and Quality

During the liquefaction clean up phase, data was reported by Fulton & Hogan's field crews and sub-contractors by using both daily reports and real time recording through portable devices. There were two methods used for data input. The first were 'Daily reports' which were completed manually on paper and where submitted to administrative support staff at the end of the day to be entered in RAMM database. Daily reports contained summary information about the jobs that was completed during the day such as location, resources used, labour hours and occasionally tonnages removed. The second type was the "Pocket RAMM" application which enabled user inputs from portable devices, such as laptops and tablets, in the field and update the database directly.

Data quality is variable throughout the assessment period of September 2010 to December 2011. The RAMM system initially lacked a suitable template to record damage assessment from liquefaction and related repair work. This created some confusion for field crews and thus inconsistencies in data collection, particularly during the clean-up following the Darfield earthquake.

Entries were input during an emergency environment, where contractors had never seen liquefaction before (at least initially) and where no previous procedure on data collection was in place. Daily report data had to be handled multiple times and rely on crew foremen recall jobs completed throughout the day, which often created errors or loss of information. Additionally, data was recorded from a wide range and large number of contractors and sub-contractors, many of whom who were not accustomed to RAMM usual reporting protocols.

Due to these challenges, some information reported from the clean-up was incomplete, not well identified or lost. For example, some road identification numbers (road ID) were missing, road names were misspelled (making it impossible to locate the job when ROAD ID was missing), a large amount of the tonnage data was lost or not recorded.

Another issue was adequately recording the liquefaction damage or work undertaken on long road segments. Within RAMM, the city roading network is divided into road sections and each section is attributed a unique Road ID. Those roads section are of various lengths. They may represent a complete road or only a section of the road. Road segments were generally delimited prior to the earthquakes. To accommodate for the new extensive clean-up and repair demand following the Christchurch 1 earthquake, there was a need for higher precision, requiring the addition and division of road segments. However, this was not done to a high enough degree and the resulting road cost averages in some cases are a diluted versions of highly concentrated liquefaction areas across that whole road segment. This is important in the data analysis, as an average of the clean-up over the whole road section may not reflect reality.

4.2. Methodology

This section provides a general description of the method used to analyse the data. It was first filtered to represent only activities related to the liquefaction ejecta clean-up and then manipulate to obtain temporal values such as general cost, hours and number of roads cleaned per day, resources costs and hours per day and numbers of roads cleaned per day. The values were also rearranged to spatially illustrate the liquefaction ejecta clean-up in Christchurch using ArcGIS.

4.2.1. Data Filtering

The data available covered only the three first major liquefaction ejecta events (4 September 2010 (Darfield), 22 February 2011 (Christchurch 1) and 13 June 2011 (Christchurch 2)). Data ranges from 4 September 2010 to 5 December 2011 and covers at least 16 weeks following each event. It contained over 18,000 entries in total (5,457 post-Darfield earthquake and 12,628 post-Christchurch 1). In order to quantify the clean-up of the city during this time period, the data had to be filtered to only represent work related to the roads and properties clean-up activity (Figure 17). This section presents the method used to filter the data as well as important assumptions that were made during the data analysis process. An extended method is presented in Appendix F.

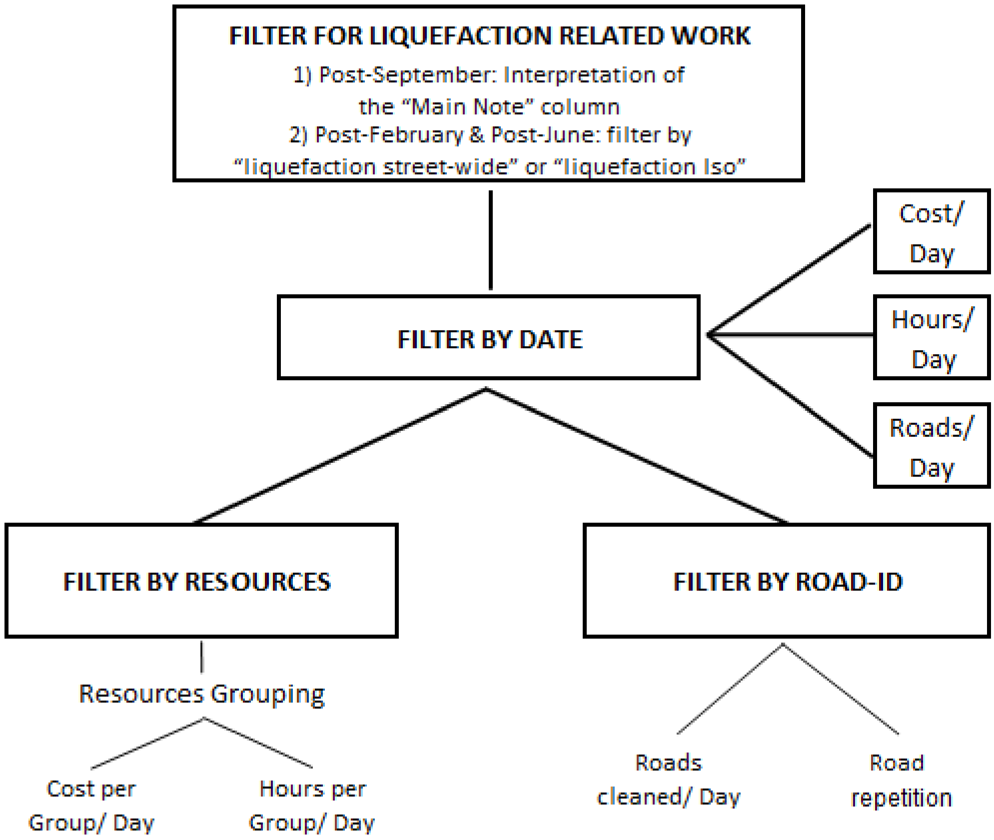


FIGURE 17: DATA FILTERING PROCEDURES

The procedure used to filter the data included three steps. The first step objective was to clean the data to only represent claims related to liquefaction ejecta clean-up, usually called ejecta or mud by contractors. Claims with no dates or no costs associated with it where deleted. For the Darfield clean-up period, data were filtered using key words such as liquefaction, ejecta, sand, mud or clean-up. For the Christchurch 1 and Christchurch 2 clean-up period, data entry had been upgraded to accommodate the new type of work related to earthquake damage, including liquefaction ejecta clean-up. A validation of the "ROAD ID" was performed, as this acts as the primary location and task identifier for the dataset (i.e. acts as a primary key for the database). This was done by filtering for jobs without a "ROAD ID" associated with it. It was observed that for those jobs, roads were identified in the "Main Note" column. This was mostly observed for the Darfield clean-up period and was assumed to be a result of the lack of suitable template and experience for data collection. The RAMM road ID associated with the roads present in the "Main Note" columns was added to the table to facilitate further filtering. Thirty percent of the roads data claims and 35% of costs data had to be redefined for the Darfield clean-up period data. For the data Christchurch 1, most of the claims had a road ID associated with it (24% of the roads and 9% of the costs for Christchurch 1 and 1% of the roads and the costs for Christchurch 2). When a road ID was provided, it was directly used even if more roads were defined in the main descriptions. For this reason, the data must be looked at as a general area around the roads rather than a direct reflection of the road clean-up.

Then, once a general filter had been completed, the second step was to filter the data by date. The date used represented the day the work was completed. From this stage it was possible to calculate general cost/day, hours worked/day and the number of road cleaned/day.

For the third step, the data was filtered by resources and by ROAD ID. From there, worked hours and costs related to resources per day and street per day could be calculated. At this stage, the "main note" entry was reviewed to identify any additional information about tonnages collected or resources used that had been added as a comment. A wide range of different resources were used during the clean-up operations, so these were grouped into categories (Table 13). Excavators, loaders and Bob-Cats were grouped to represent the clean-up of the road, by handling and digging. The trucks represent the transport and carting of materials. The water cart and the cleaner were grouped to represent the washing and the dampening of the streets and pathways. All machineries hours include a driver.

Once the data was filtered and preliminary tables and graphs were produced, a visit to Fulton & Hogan was organised with Dan Lucas to validate and confirm the results. It was important that the representative of Fulton & Hogan had been an active participant in the clean-up management during the past events and it is an important part of the risk management framework to communicate and consult with agencies.

4.2.2. Data Analysis

By filtering by road ID, it was possible to identify the roads that were cleaned on different days, the repetition of road clean-up as well as spatial distribution and evolution of the clean-up. Those resources were used to quantify the Christchurch clean-up while the unique Road IDs were used to geospatially map the evolution of the clean-up. A snapshot of tonnages removed from the street was available for the first week of March and was used to create a focussed detailed analysis.

TABLE 13: RESOURCES GROUPING AND DESCRIPTION

Grouping		Description	Resources in the group
Clean-up, handling and digging	Excavator	Used for digging and liquefaction handling	5, 10, 15, 20, 30 ton, Bulldozer (D6).
	Loader	Used to load and transport material	5, 7-10, 15 ton, Telehandler
	Bob-cat	clean-up of the road, by handling and digging	Bob-cat mill 1m head
Transport and carting	Trucks	transport and carting of materials	4x2, 6 and 8 Wheel, Articulated, truck & trailer.
Crew and Machinery transport	Transporter	transport and carting of materials	
	Ute	Labour transport	
Washing and dampening	Water Cart 10000 ltr	Washing and the dampening of the streets	Water Cart 10000 ltr
	Washer	Washing and the dampening of the streets	Bob cat broom, tractor broom, Suction sweeper, Sump sucker (Gully truck), Waterblaster, Sprayer truck.
	Labour all	Labour hours	
	Grader	Filling and road repairs	Grader, PTR, Paver 5 and 10 ton Roller/Compressor, Pedestrian roller, Hoe Pack Compactor, RAMMEX Trench Compactor Sheep's Foot Compactor.
Associated material	Materials	Tonnage of ejecta remove from the streets as well as filling materials	AP 20 Screened. G3-G5 Chip, Bitumen (cutback) Crusher dust, Pitrum, Tack Coat, Hotmix – AC14/AC5/AC10 M3 AP65 Sub Base, M4 AP20 Topcourse, M4 AP40 Basecourse
	Water	Used to wash and damp the road	Water (from hydrant) (only started to get charged in Christchurch 2)
	Others		6-8 inch pump, Concrete Saw, Petrol tanker, Hiab, Petrol breaker, Traffic Management truck, Fencing, signs, cones, 45kg, 60kg, 330kg reversible plates

4.3. Results and Analysis

This section presents the cost and resources results as well as the analysis produced with the RAMM dataset from the Christchurch clean-up following three liquefaction ejecta events with three different ejecta volumes, distributions across the city and clean-up experience. It will present the resources and costs values for the clean-up of Christchurch, a general overview of the clean-up evolution of the whole sequence of earthquakes followed by a comparative and spatial analysis of the evolution of the clean-up through time considering cost, repetition and volume.

4.3.1. Resources and Cost of the Clean-up

This section presents the overall costs and resources used for the clean-up of the three liquefaction ejecta events based on the data provided by *Fulton and Hogan*. It presents a revised cost estimates for the whole sequence clean-up based on the RAMM data analysis results. All the costs presented in this section are in $NZ.

The total cost and hours were obtained following data filtering of resources in RAMM and do not include material costs (Table 14). From these data, the average clean-up cost for those three liquefaction ejecta event was about $NZ 85/hour with a minimum of $NZ 69/hour in Darfield and a maximum of NZ$ 91/hour in Christchurch 2.

The resource cost distribution over the whole sequence clean-up show that the most expensive activities in descending order were the transport and cartage of ejecta out of the streets, the handling of the ejecta, the labour and washing/watering of the streets (Table 15).

TABLE 14: TOTAL COSTS AND HOURS FOR THE THREE MAJORS EVENTS

	Total	Darfield	Christchurch 1	Christchurch 2
Hours	142 784	24 078	87 276	31 429
Cost ($NZ)	$NZ 12,105,837	$NZ 1,669,947	$NZ 7,585,749	$NZ 2,850,140
Cost per hour	**85**	**69**	**87**	**91**

TABLE 15: DISTRIBUTION OF THE RESOURCES COST OVER THE WHOLE SEQUENCE CLEAN-UP

Resources	Cost ($NZ)
Trucks	$ 5,187,146
Excavator/Loader/Bob-Cat	$ 3,371,380
Labour	$ 1,407,387
Washing	$ 951,800

An average cost per km for each week was calculated and are presented in Figure 18 andTable 17. In order to get a representative cost per kilometer using weekly values, the road length was multiplied by the amount of time the street segment was cleaned during the week using the following formula:

$$\frac{Cost}{Length\ of\ the\ road\ x\ Repetition}$$

Clean-up following the Christchurch 2 earthquake has the highest cost/km around week 6, 9 and 16 ($NZ 13,028/km, $NZ 12,342/km, $NZ 9,441/km) while Christchurch 1 has an increase at the beginning then it stabilised from week 4 to 11 and drops to a relatively low cost per km from week 12 to 16 and Darfield is highly irregular and has the most expensive clean-up cost/ km.

The cost/km is highly variable throughout the events with no clear trend. The mean cost/km for the entire clean-up ranges between $NZ 5,500 /km for the Darfield clean-up and $NZ 11,650 /km for the Christchurch 1 clean-up. It is expected that the cost/km will be highly variable due to the difference in road segment length and volumes of sediment affecting the street. Some long roads could have been affected only on a small section and dividing the cost on the whole street under estimate the real cost of the clean-up. In order to limit errors due to this problem, the mean and the standard deviation were calculated for the length of road, the cost associated with the road and on the cost/km. The results are presented in Appendix H.

TABLE 16: ESTIMATED COSTS REVIEWED FROM THE QUANTITATIVE STUDY OF LIQUEFACTION CLEAN UP FOLLOWING THE 4 SEPT 2010, 22 FEB AND 13 JUNE 2011 EARTHQUAKES IN CHRISTCHURCH.

Items	Estimated costs ($NZ)	
	Subtotal	Total
Transportation Costs for calculation	550,000 tonnes of ejecta at an average of $0,28/km/tonne ($5.50/T)*	$ 3,036,000.00
Disposal Site Infrastructure		$ 800,000.00
Disposal Site Running Costs	$500,000 *(est. post 4 Sept 2010)* $1,200,000 *(1 month post 22 Feb 2011)* $500,000 *(est. post 13 June 2011)*	$ 2,200,000.00
Disposal Cost	550,000 tonnes of ejecta at 5$ per tonne	$ 2,750,000.00
Contractor Staff Time Contractor Operation Cost	$12,106,000 Fulton Hogan $15,000,000 City Care (surface clean-up of the northern city area)	$ 27,106,000.00
Estimated Volunteers Labour Contribution	$1,000,000 (Student Army) $1,000,000 (Farmy Army)	$ 2,000,000.00
Donation to the Student Army	$20,000 MSD $10,000 Mitre 10/ANZ: wheelbarrows $30,000 (other)	$ 60,000.00
Total estimated costs		**$NZ 39,952,000.00**

*Based on Johnston 2001 calculation

*Most of the information were based on personal communication except for the Fulton and Hogan RAMM data analysis cost.

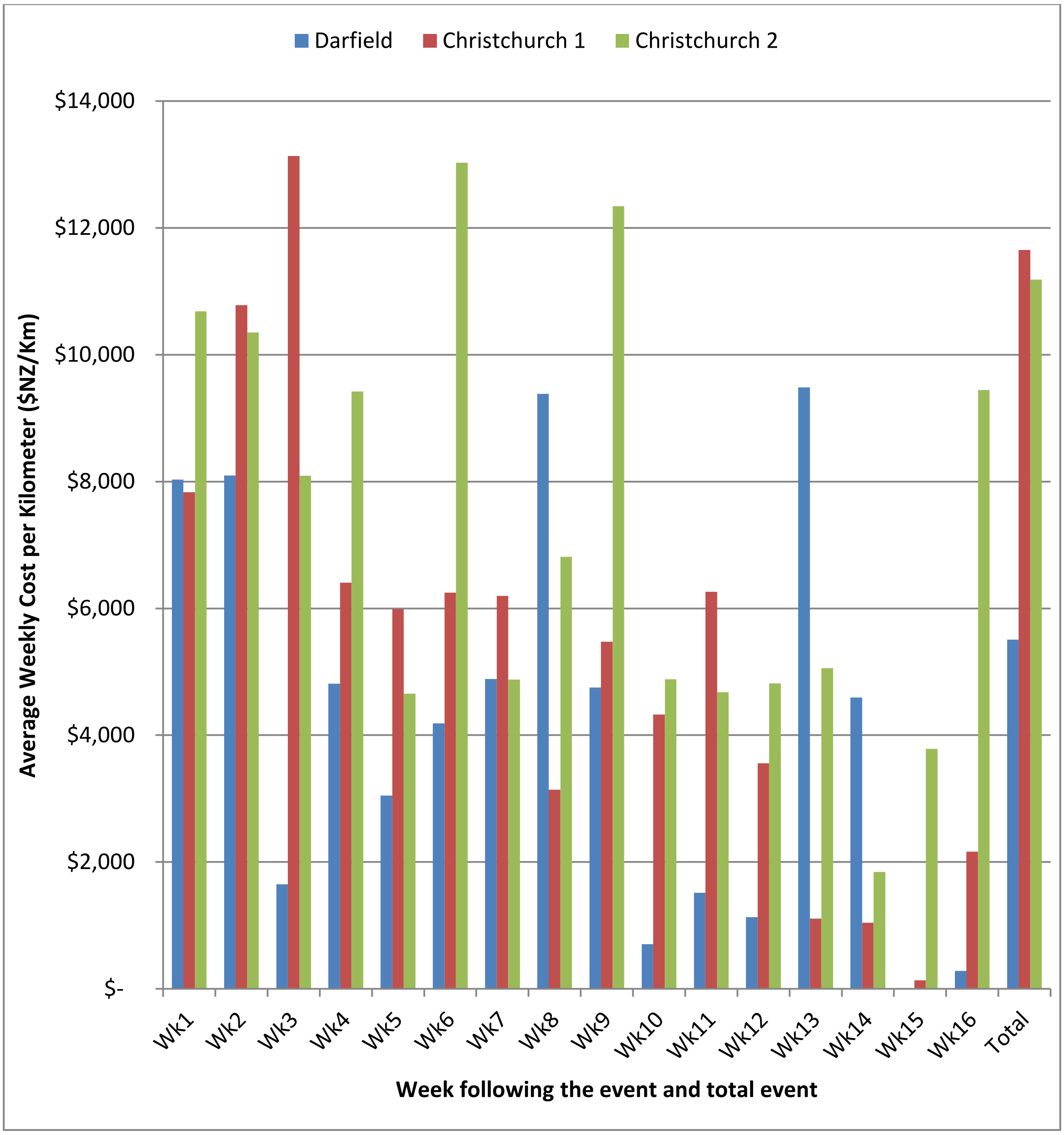


FIGURE 18: COMPARISON OF THE AVERAGE WEEKLY COST PER KILOMETRE

TABLE 17: WEEKLY AVERAGE COST PER KILOMETRE VALUES

Weeks	Events Average Cost per km ($NZ/km)		
	Darfield	Christchurch 1	Christchurch 2
Wk1	8,029	7,830	10,686
Wk2	8,095	10,780	10,353
Wk3	1,651	13,133	8,092
Wk4	4,814	6,406	9,420
Wk5	3,048	5,989	4,655
Wk6	4,187	6,249	13,028
Wk7	4,885	6,195	4,879
Wk8	9,383	3,142	6,812
Wk9	4,751	5,475	12,342
Wk10	703	4,326	4,884
Wk11	1,517	6,260	4,679
Wk12	1,133	3,556	4,816
Wk13	9,483	1,107	5,056
Wk14	4,596	1,042	1,844
Wk15	N/A	133	3,784
Wk16	284	2,164	9,441
Total	**5,508**	**11,650**	**11,185**

4.3.2. Canterbury Sequence Clean-Up Temporal Evolution Analysis

This section presents the analysis produced from analysis of the RAMM dataset from the Christchurch clean-up following liquefaction ejecta events through time. It presents the evolution of the cost, hours, resources and numbers of roads cleaned per day throughout the events and compares them for the three clean-up periods.

Figure 19 and Figure 20 represents the evolution of the clean-up through time from the 4 September 2010 to the 5 December 2011 using different information such as cost and number of street segments (from RAMM) cleaned-up per day (Figure 19). More detailed graphs showing the hours per day for transport resources (trucks), cleaning resources (excavators/ loaders/ bob-cat) and washing resources (water-cart/ washers) are presented in (Figure 20).

Variation of costs and resources hours are presented daily in (Figure 18) and (Figure 19) throughout the analysis period. The distribution of the cost for each event is represented by a slow start of one to two days, followed by a rapid increase in clean-up response until it reached a maximum peak. Clean-up cost, hours and activity remains relatively high for several weeks but revert to consistently low levels until the next liquefaction inducing earthquake. It also shows that the Darfield clean-up was more complex than the Christchurch 1 and Christchurch 2 clean-up, which we attribute to greater time needed for planning and coordination.

From the graphs in Figure 18 and Figure 19, it is possible to observe a clear difference in the costs, roads and resources between the three liquefaction ejecta clean-up. The Darfield and Christchurch 2 liquefaction ejecta clean-up period present lower costs and resources used then Christchurch 1 clean-up period. The highest cost peak for the Christchurch 1 clean-up is more than doubled the highest cost peaks of the other clean-up periods.

By comparing the cost per day to the number of roads cleaned per day, it is possible to observe that the distributions generally correlate (Coefficient of determination equal to 0.94 (Appendix J.1)) despite some of the high cost peaks not being reflected in the roads graphs.

The data in Figure 18 and Figure 19 agrees with Fulton Hogan’s approach of reducing staff workloads as the top priority jobs were completed (i.e. main arterial roads cleared). Workers were encouraged to take the weekends off and go back to a normal work schedule, which can be observed by a decrease in activities during the weekends (Appendix I).

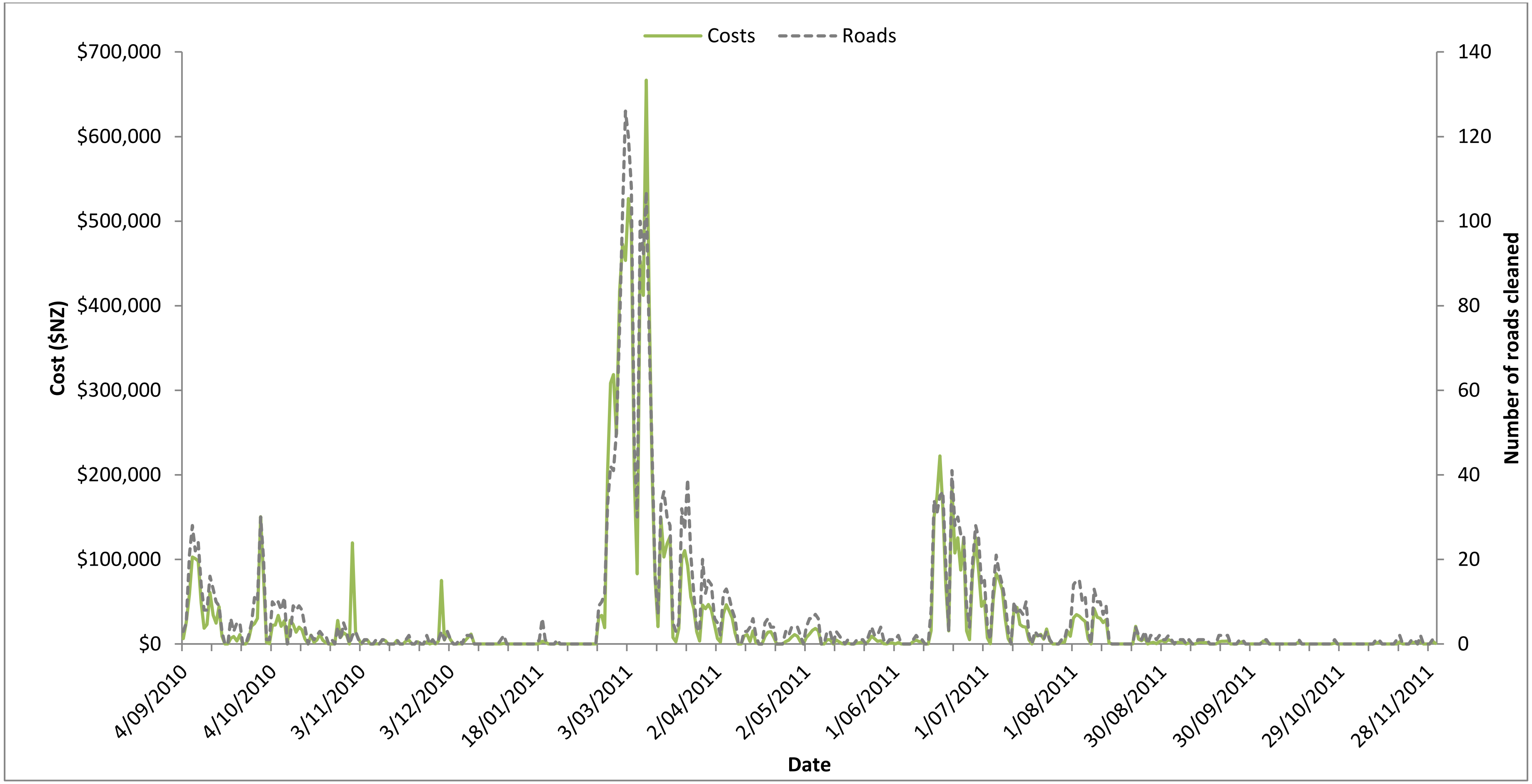


FIGURE 19: EVOLUTION OF THE LIQUEFACTION CLEAN-UP COST AND ROAD CLEANED-UP FOR THE PERIOD OF 4TH SEPTEMBER 2010 TO DECEMBER 2011

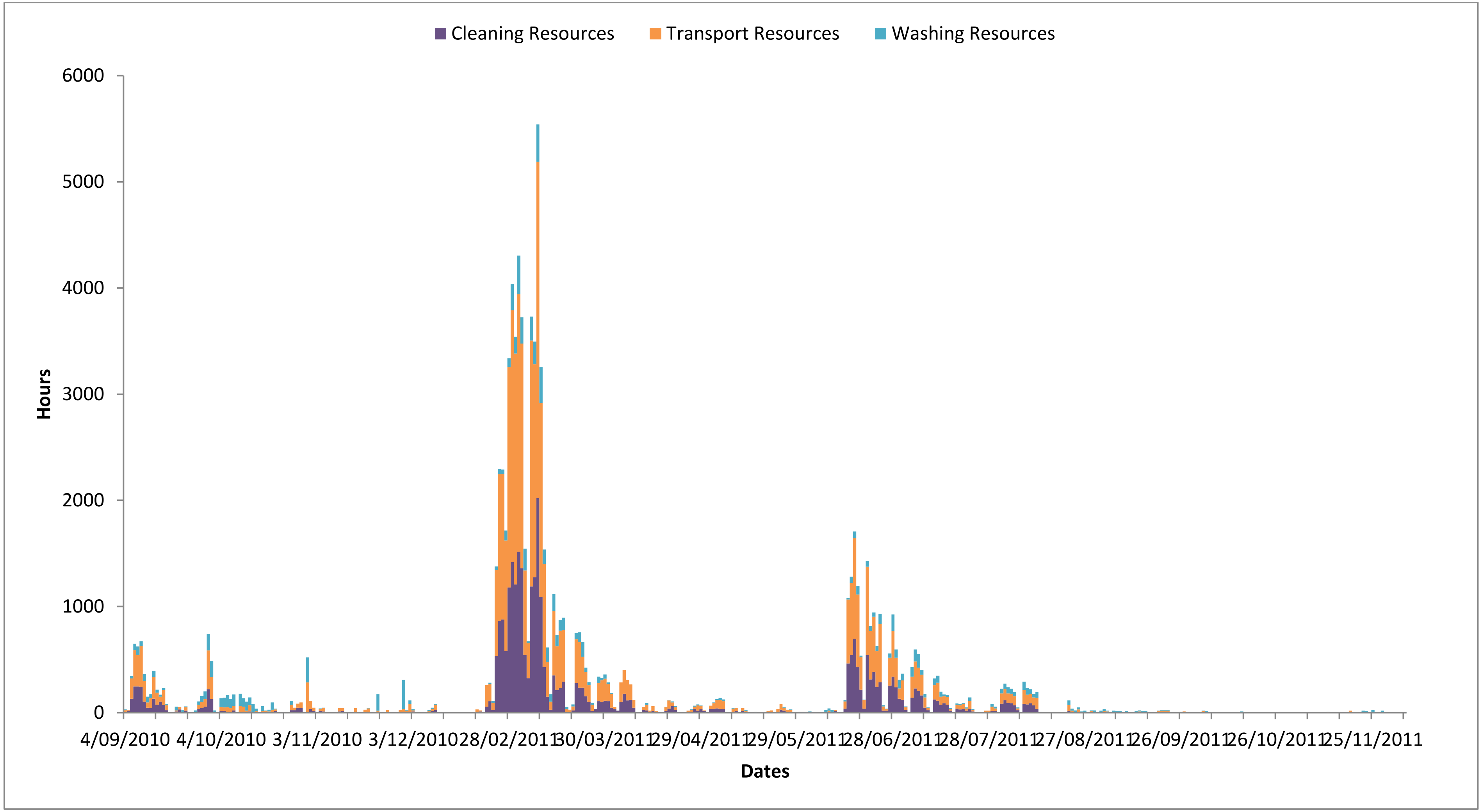


Figure 20: Evolution of the Resources used for the Liquefaction Clean-up for the period of the 4th of September 2010 to December 2011

This was done by comparing the costs, hours and resources for the first hundred days following each major liquefaction event. In order to aid analysis, the cleaning resources (excavator, loader, Bob-Cat) and the washing (water cart, suction sweeper, cleaning broom) resources were combined as one resource and are presented in Appendix K.

From the cost comparison graph (Figure 21), it is possible to see that the Darfield daily clean-up cost was more irregular compared to the Christchurch 1 and Christchurch two clean-ups. Darfield clean-up cost distribution has four peaks, while Christchurch 1 clean-up period cost is represented by one curve and Christchurch 2 clean-up period cost by two curves. It is possible to see from the graph that there was a delay of a few days (two to four days) before the peak costs for all three events. There is a huge initial response that usually lasted for the first few weeks, then, there is a slow decrease in clean-up evolution followed by a low plateau after about 60 days. There are a lot of external factors to take into consideration when looking at these graphs, such as days off taken by the contractors and decision making effects represented by a slowdown in the clean-up or a low peak within the graph. Pauses in activity reflect time taken by the clean-up management team to formulate clean-up plans and tactics as well as consulting with CCC on priorities and costs. Those pauses provided opportunities for other activities such as road repairs to be done. From the cost graphs (Figure 21) it is possible to say that after about a month (30 days), the costs per day expected would be lower than $NZ 50,000 and after two months (60 days), lower than $NZ 25,000.

Looking at the comparison of the number of streets cleaned per day (Figure 22), the Darfield clean-up has only two major peaks, an initial peak and one 27 days following the Darfield earthquake, which are then followed by a slow decrease. The Christchurch 1 curve is more uniform with only a major initial peak and a slow decrease. The Christchurch 2 curve also has two peaks with an initial long and spread peak and a later sharp peak around 48 days following the event.

To facilitate construction of best-fit curves, representative data values were selected that summarized activity in a given period (state the period). It was not possible to identify a direct statistical relation between the costs and the time for each earthquake because of the high variation from one day to another. Attempts were made to uniform the clean-up action to then be able to represent the clean-up cost in relation to the time since the event using a mathematical formula. A selection of cost values, thought to be the most representative and limiting the impacts of slower days when contractors were encouraged to take a day off, was used to represent the general curves. The curves were separated in two, the ascent and the decay. The ascent represent the cost from the event to the maximum cost, the decay represent the clean-up from the maximum cost to the consistent low level of activities. The selection of the maximum cost peak from Christchurch 1 was on day 9 rather than day 15, because this peak is not present in other graphs. Best fit trending lines of the values are presented in (Figure 23) with their equations in Table 21. A linear curve (thick line) was used to represent the ascent of the costs from the beginning of the event until the maximum cost. The decay from the maximum cost until a consistent low level of activity is represented by exponential curves (dashed lines). The lines from both graphs for each event are relatively similar. The Christchurch 2 linear formula is the steepest curve while the Darfield represent the shallowest one, representing the two rise to the maximum cost extremes (fast and slow). The exponential curves of the selected values fit nicely the slow decay to normal background and closely represent the maximum costs so they are considered as good representative of the costs evolution for each event and could be potential representative of the costs decay following a fine grained sediment (<1 mm) producing event. The gradient of the ascent period has steepened over all of the clean-up events, implying there has been improvement in response time throughout the sequence.

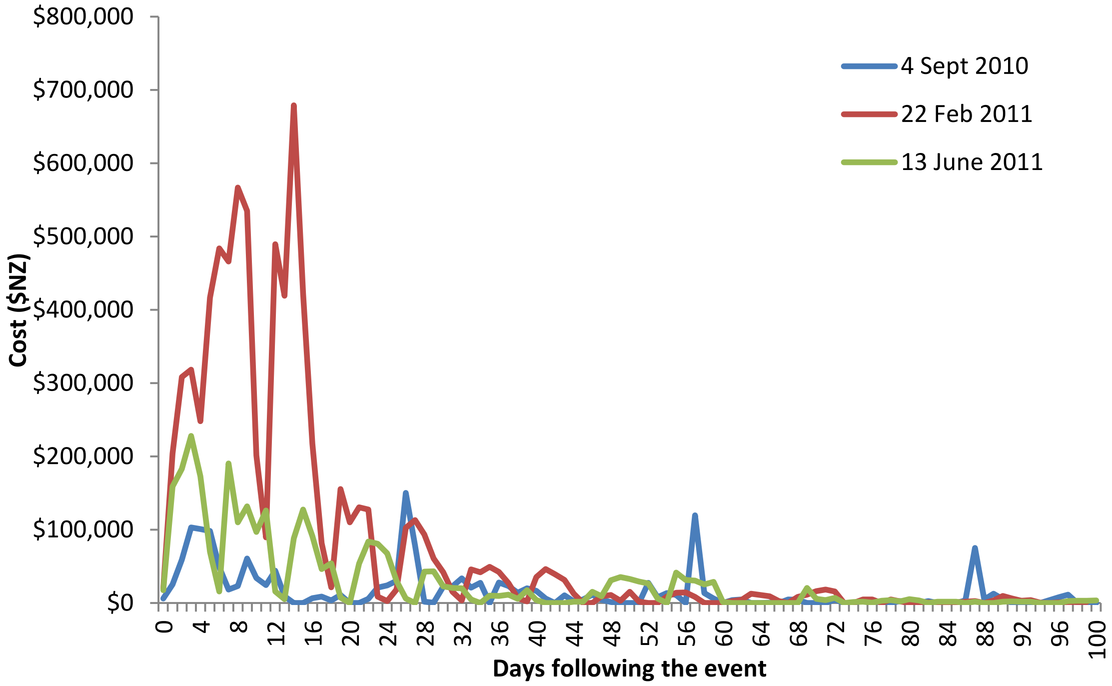


Figure 21: Comparison of the clean-up costs following liquefaction generating events in Christchurch 2010-2011 earthquakes sequence

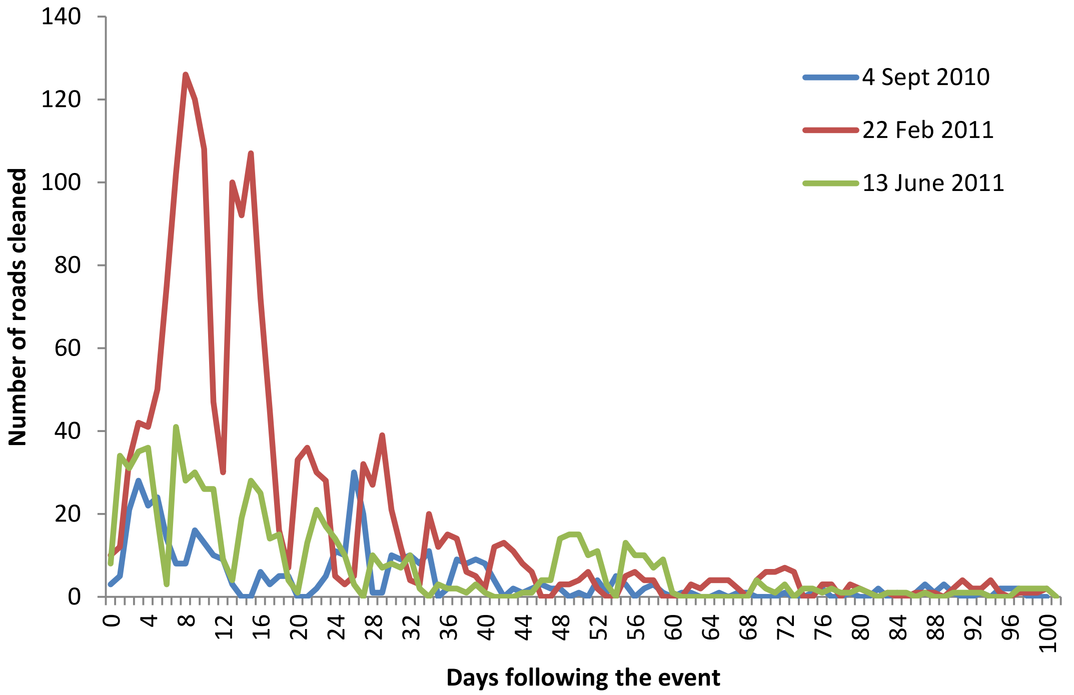


Figure 22: Comparison of the clean-up evolution following liquefaction generating events in Christchurch 2010-2011 earthquakes sequence using the number of roads cleaned per day

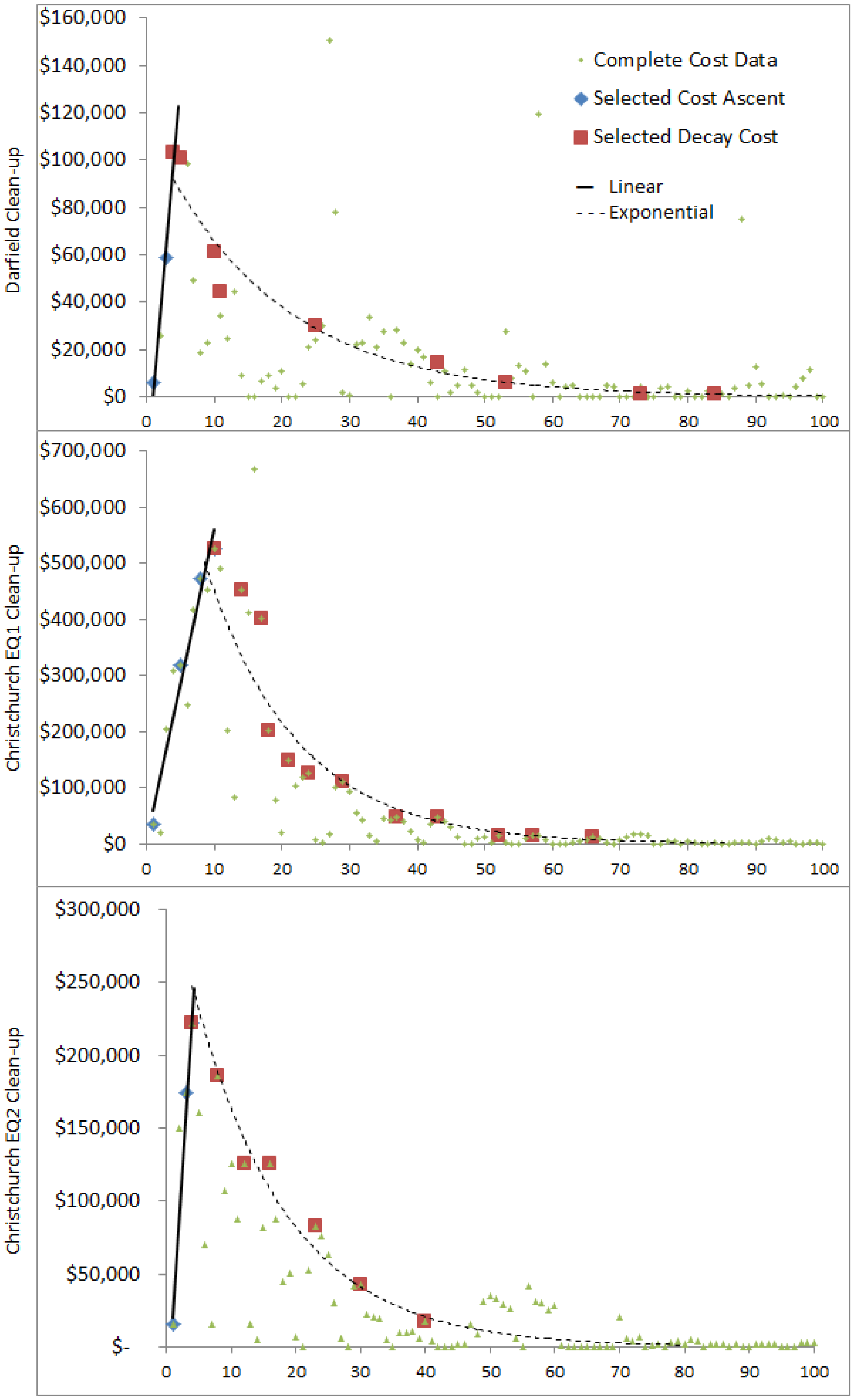


FIGURE 23: GRAPHS OF THE BEST FIT CURVES FOR THE ASCENT AND DECAY OF THE COSTS EVOLUTION THROUGH TIME FOR THE 3 MAJOR EVENTS FOR THE SELECTED VALUES

TABLE 18: COST EVOLUTION THROUGH TIME BEST FIT CURVE EQUATIONS FOR THE THREE MAJOR LIQUEFACTION EJECTA CLEAN-UP

Clean-up Period	Linear Equations for Cost Ascent Approximation	Exponential Equations for Cost Decay Approximation
Darfield	$y = 31370x - 27632$ $R^2 = 0.9805$	$y = 114267e^{-0.055x}$ $R^2 = 0.9791$
Christchurch 1	$y = 55740x + 3478.9$ $R^2 = 0.9749$	$y = 937071e^{-0.073x}$ $R^2 = 0.9682$
Christchurch 2	$y = 70409x - 50266$ $R^2 = 0.988$	$y = 325986e^{-0.069x}$ $R^2 = 0.973$
Where,	*x = Cost in $NZ* *y = Days following the event*	

4.3.3. Cumulative Comparative Analysis

The cumulative percentage of costs and number of roads cleaned per day for each event were plotted on a graph to compare clean-up response of each event. Cumulative percentage curves are commonly used to demonstrate the value distribution and determine the number of observations that lie above or below a particular value of interest. It is used here to present the percentage of the total cost and numbers of roads cleaned with time following the three major liquefaction ejecta events (Darfield, Christchurch 1 and Christchurch 2). A time frame of 100 days was used for the data analysis because it could capture the full behaviour of the clean-up. This section will cover a general overview of the graphs followed by a description of the concentrated regions created by the data distribution of the combined data plots and their best fit curves. Figure 24 and Figure 25 show the evolution of the clean-up by looking at the cumulative percentages of the costs and number of roads cleaned per day.

The calculated cumulative percentage data plots were smoothed out by best fit curves for each earthquake clean-up period for both the cost and number of road cleaned graphs (Figure 24 and Figure 25). The equations are presented in Table 21. An advantage of displaying the best fit curve is that it allows an idealised fit of the clean-up time or cost, without the minor irregularities (caused by irregular contractor working hours, clean up method experimentation and other such complications) to be observed (see Chapter 3). Figures 25 and 26 both contain two areas defined in pink and yellow. Together the yellow and pink zones make up the total range of the data for the events. The pink zone illustrates the separation of the upper and lower best fit curves.

These zones were created for the purpose of rapid comparison of the information within and between graphs. The zones can be interpreted in together as follows: A widely spread pink zone indicates that the average data curves of each event differ more, a narrow pink zone means that the best fit curves and the bulk of all the data is closer together.

The initial clean-up cost curves are comparable for each event until day 10, where they separate. From this analysis it can be observed that 50% of all the costs were used within the first 15 days for the Christchurch 1 and Christchurch 2 events, and within 25 days for the Darfield event. Approximately 75% of costs were reached within the first 15 to 25 days for Christchurch 1 and Christchurch 2 but it was up 40 days for Darfield. The Darfield curve represents a longer period of sustained clean up activity, and thus costs were more spread out over the clean-up period. Christchurch 1 and the Christchurch 2 earthquake have 97% of the cost is reached after 60 days rather than 90 days for the Darfield clean-up. The increase in clean-up efficiency may be attributed to the experience gained with the Darfield clean-up event.

The comparative cumulative graph (Figure 25) for the evolution of the amount of roads being cleaned differs most significantly in the distribution of the data from the cumulative cost graph (Figure 24). The curves are closer together in Figure 25 and this shows that the evolutions of the road clean-up are similar for the three events. From this graph, it is possible to tell that 40% of the roads were cleaned after 10 days, 50% after 2-3 weeks and 90% after 40-55 days.

Based on those different curves, Table 19 and Table 20 presents the percentage cost and number of road cleaned-up values with time following a fine grained sediment (<1 mm) deposition. From this, we can say that past two weeks following a fine grained deposition event in Christchurch, 30-70% of the total costs are expected to have been spent, after one month 53-93% and after two months, 85-98%. For the roads, after two weeks, 30-60% of the roads would have been cleaned, 60-85% after one month and 85-95% after two months.

In conclusion, this section illustrates the efficiency gained from the Darfield clean-up to the Christchurch 2 clean-up. Considering the large volume difference between the three events, the area controlled by the numbers of roads cleaned is narrow relative to the cost curve, suggesting that the evolution of the road clean-up is more predictable then the clean-up costs. Caution is advice in any application of these results regarding forecasting events across different types of fine grained sediments because fine sediment varies and the ease of clean-up (transport and storage) are depending on their geotechnical properties, hence to volume, extension and time would differs. Even for potential applications of liquefaction events in Christchurch, caution is also advised.

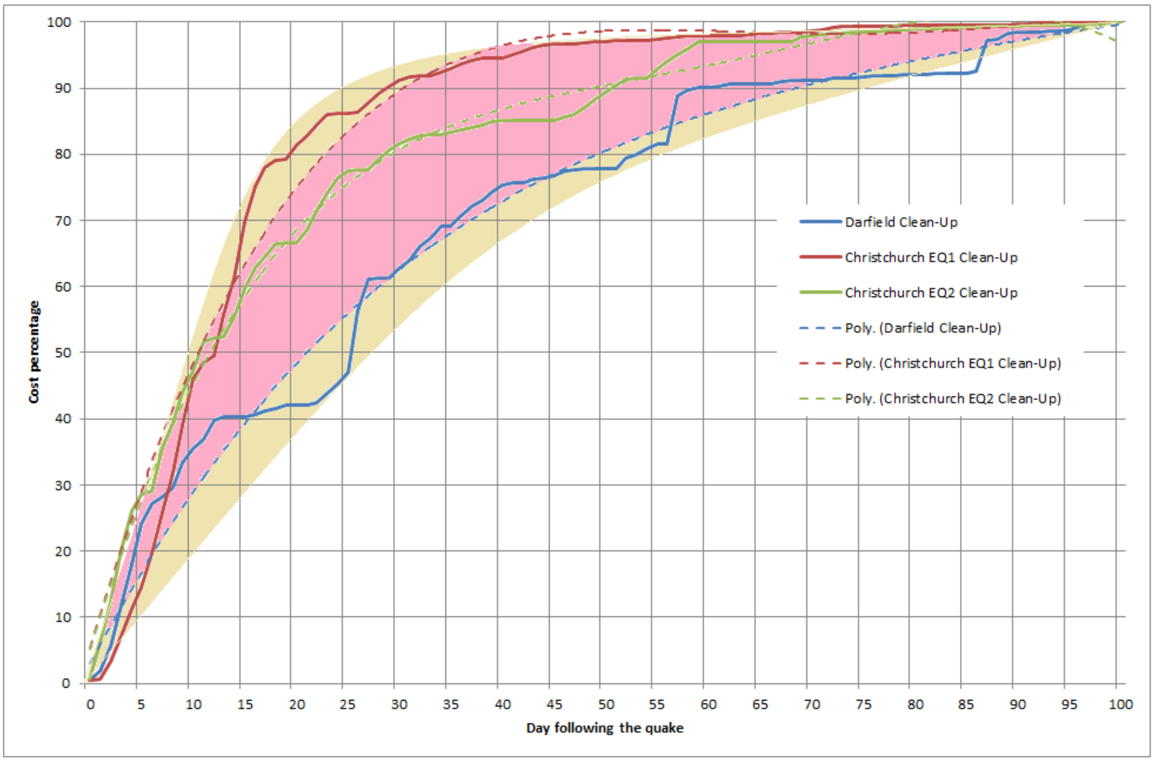


FIGURE 24: COMPARATIVE PLOT OF THE CUMULATIVE COST FOLLOWING THE QUAKES. THE SHADED AREAS REPRESENT THE EXTREME BOUNDARIES FOR CHRISTCHURCH CLEAN-UP COST EVOLUTION

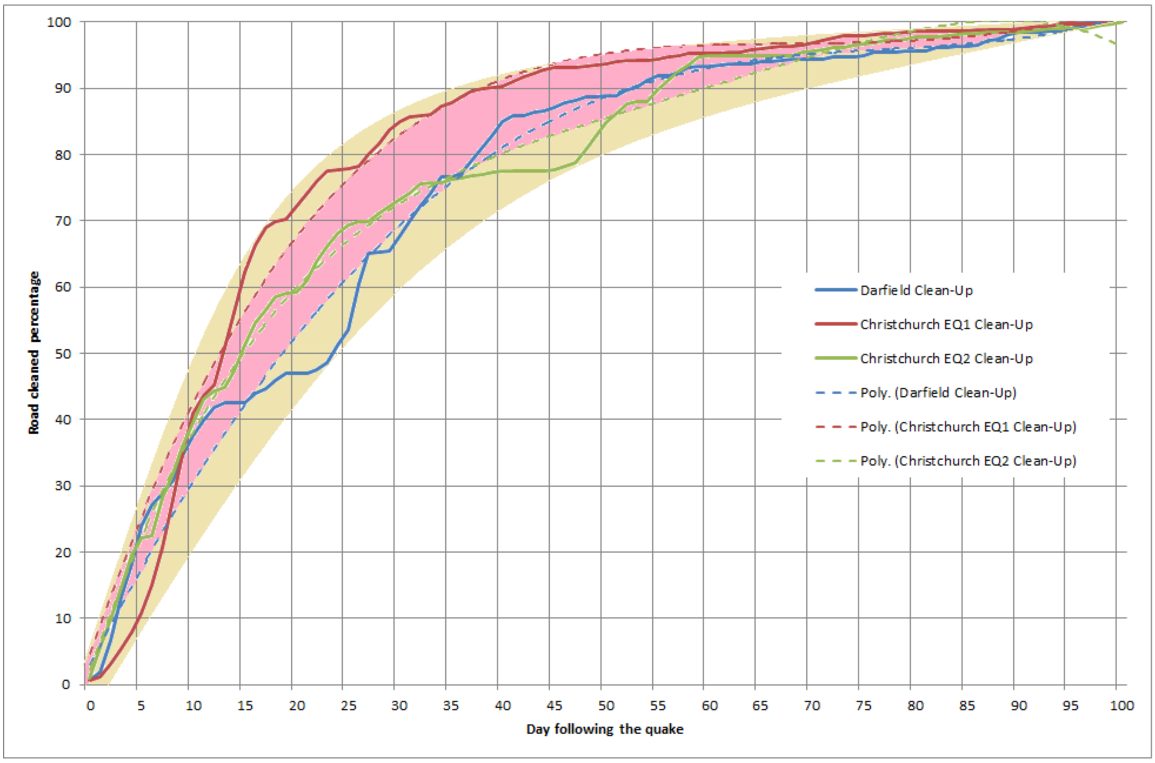


FIGURE 25: COMPARATIVE PLOT OF THE CUMULATIVE ROADS CLEANED FOLLOWING THE QUAKES. THE SHADED AREAS REPRESENTS THE EXTREME BOUNDARIES FOR CHRISTCHURCH THE CLEAN-UP EVOLUTION

TABLE 19: TIME NEEDED TO ACHIEVE A SELECTED CUMULATIVE PERCENTAGE OF COST AND ROAD CLEANED

	Cost				Roads			
Percentage of total	**25%**	**50%**	**75%**	**90%**	**25%**	**50%**	**75%**	**90%**
Numbers of days (x-axis range)								
'Yellow'zone	4-13	10-28	16-48	25-75	5-12	11-24	20-43	35-70
'Pink' zone	5-8	11-22	20-43	31-70	6-8	13-18	24-35	39-60

TABLE 20: ACCUMULATION OF COST AND NUMBER OF ROAD CLEANED OVER A PERIOD OF A HUNDRED DAYS

	Cost				Roads			
Days	**5**	**15**	**30**	**60**	**5**	**15**	**30**	**60**
Percentage achieved (%) (y-axis range)								
'Yellow'zone	10-28	28-72	54-94	83-99	9-27	31-64	58-86	86-96
'Pink' zone	15-28	38-62	62-89	86-99	15-22	42-55	68-83	90-96

TABLE 21: COMPARATIVE CUMULATIVE COST CURVE EQUATION

Clean-up period	Best fit curve equation and coefficient of determination
Darfield Clean-up	$y = -0.0000008x^4 + 0.0003x^3 - 0.0419x^2 + 3.0545x$ $R^2 = 0.9826$
Christchurch 1 Clean-up	$y = -0.000003x^4 + 0.001x^3 - 0.1115x^2 + 5.5083x$ $R^2 = 0.9717$
Christchurch 2 Clean-up	$y = -0.000006x^4 + 0.0014x^3 - 0.1254x^2 + 5.3387x$ $R^2 = 0.9937$
Where,	*x = Days following the event* *y = Value percentage (cost or road cleaned)*

4.3.4. Volume Analysis

This section attempts to analyse the volume of liquefaction ejecta in the clean-up of Christchurch. Unfortunately, there was not a complete dataset of volume cleaned from the roads available from RAMM for the full city or for the entire time period of the whole clean-up. Data used was provided from the two major contractors in separate formats and databases (Fulton & Hogan Ltd. provided volumes per day by streets and City Care Ltd. provided volumes per day by suburbs). This is in the context of an estimated > 500,000 tonnes of liquefaction ejecta removed from the city to Burwood landfill.

4.3.4.1. Fulton & Hogan Data Analysis

Fulton and Hogan volume data was limited. There was only a small snapshot of 8 days data in early March that was available within RAMM as well as some extra information derived from the contractor notes to increase the precision of the results,. From those, a case study was done.

4.3.4.1.1. Data

The original data given by *Fulton and Hogan* contained 113 values over five days from the 1st to the 8th of March 2011. From those values, 35 had a cost related to it from the RAMM data. The total tonnage from this dataset of 113 entries is 28,728 t. The data derived from the “Main note” section had to be manipulated when jobs were spread on multiple days because the description with the same tonnage was added to the attributed street. The method used to manipulate the data is presented in appendix A. From the “main note” (extracted), 92 new tonnage values were extracted. From those values, 70 had a cost related to it from which a cost per tonnage could be calculated and 80 of them were located within the small snapshot timeframe. The sum of tonnages within the “Main Note” section is 9 070 tonnes and 5 618 tonnes from the 80 values located between the 1st and the 8th of March. The data provided was used to determine the cost per volume of the clean-up and analyse the volume cleaned per street per day for the first week of March 2011.

4.3.4.1.2. Analysis

An analysis of the cost per tonne was performed for the month of March by using all the values that were associated with a cost from the original version given by *Fulton and Hogan* (original), values derived from the contractor notes (derived) as well as a compilation of both dataset (original + derived). The average costs were calculated for four different hazard categories related to the volume cleaned (small, medium and large volumes categories correspond to > 100 t, 101-500 t and > 500 t). Those values are approximation based on volume impacts for an average size property (Appendix O). Results are presented in Table 22.From those data we can say that the cost per ton for a large volume of sediment (> 500 t) will range from $NZ 2 to 13/t, from $NZ 17-28/t for a moderate volume (101 – 500 t) and from $NZ 58-113/t for a small volume (< 100 t). The average cost from all the values regardless of hazard categories is $NZ 71/t. The smaller cost related to a large volume is mostly due to the smaller quantity of data, as well as from the cost of the transport and renting of machineries. Transport and renting of machineries are the principal costs during a clean-up and thus the cost is better spread for a large volume of sediment than for a small one.

Table 22: Average cost per tonnes for the liquefaction ejecta clean-up in Christchurch

Tonnage categories	Original	Derived	Original + Derived	Average by tonnage category
	$NZ / t			
0 - 100 t	57.99	112.94	93.92	88.28
101 - 500 t	17.10	28.17	23.38	22.88
501 - 1000 t	2.35	12.71	6.14	7.07
> 1000 t	3.53	12.63	5.05	7.07
Average of all values regardless of the tonnage category	20.24	95.33	70.55	62.04

A case study from the set time window available from the provided volume data was analysed in detail from 1 March to the 8March 2011. During this time, a total of 31,462 tonnes was cleaned from 151 different street segments. A tonnage category was developed with each street segment and a map was created showing the spatial distribution of the volume cleaned for this period of time (Figure 26). The map was compared with the T&T/EQC land damage map (Figure 9). Because the T&T/EQC map represent the total land damage and the volumes only represent one week, it is not possible to draw a correlation but it is clear that large volumes were cleaned from streets located in highly impacted areas. Small volumes are located on long roads were it was assumed that only a short road section could have been cleaned. A layer showing the roads that were cleaned on the first week after the earthquake was added to compare with the volumes cleaned (Figure 27), from which, 34 had a tonnage value associated with it. Most of the red category streets (> 1000 t), where a large volume was removed, had been previously cleaned. Principal roads in the eastern suburbs such as Wainoni, Pages and Shortland only had a small amount of liquefaction removed but large total costs are associated with them ($NZ 50,000-100,000, $NZ 100,000-200,000 and $NZ 10,000 – 50,000 respectively). Other major roads such as Ferry, McCormacks and Main Road also were cleaned on multiple occasions to keep them safe and usable (Hautler, pers. Comm, 2012).

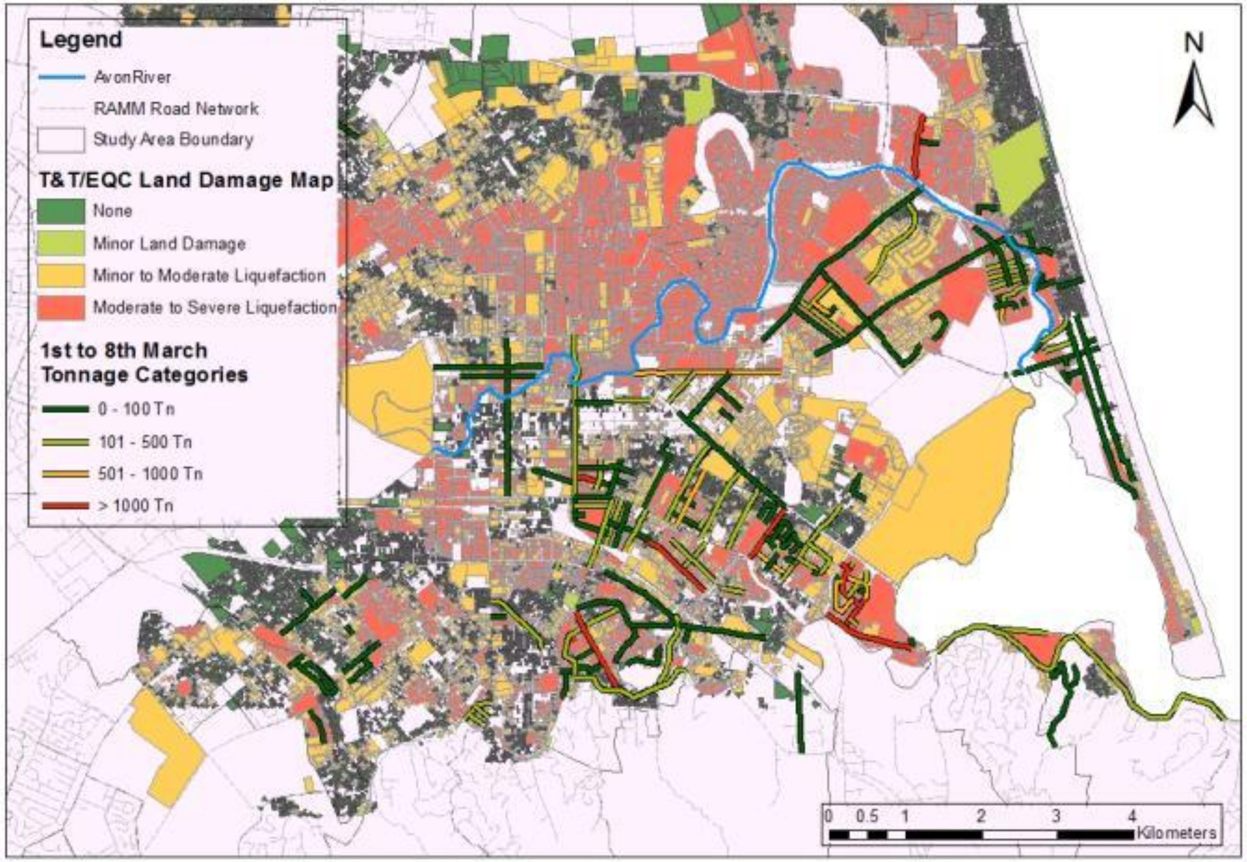


FIGURE 26: LIQUEFACTION EJECTA VOLUME MAP FROM THE MONTH OF MARCH 2011 OVERLYING THE T&T/EQC LAND DAMAGE MAP

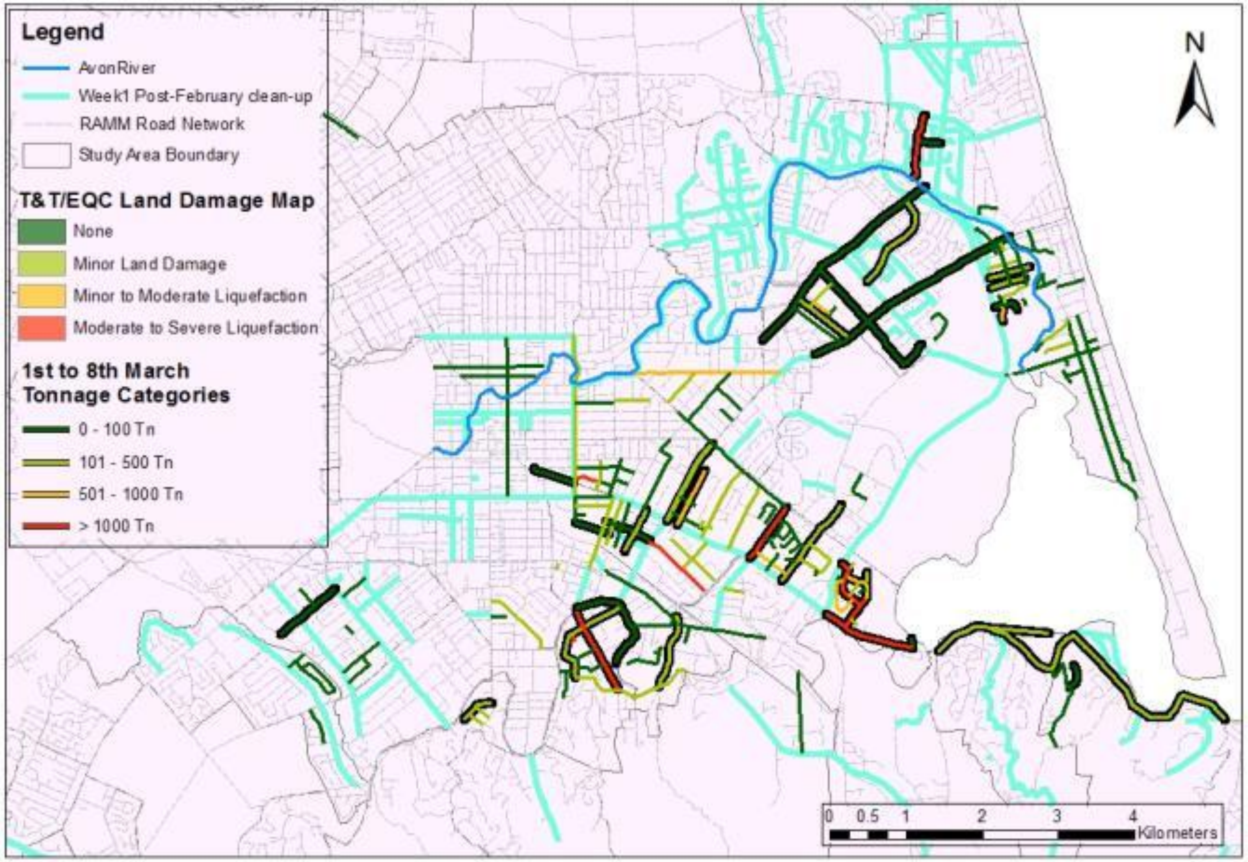


FIGURE 27: TONNAGE MAP OVERLYING THE ROADS THAT HAS BEEN CLEANED IN THE WEEK PRECEDING THE DATA

4.3.4.2. City Care Data Analysis

Some data related to the volume of liquefaction ejecta cleaned-up was also available from *City Care*. From this data it was possible to do an analysis of the clean-up cost for the Northern part of the city.

4.3.4.2.1. Data

The data available from *City Care* covered from the 23 February 2011 to the 31 March 2011. The data is split into suburbs with a daily tonnages associated with them. The data is summarized on a daily basis in Figure 28. It covers 17 suburbs and some Fulton & Hogan areas. The location of the clean-up located in the *Fulton & Hogan* area was not specified. A total of 80,517 t of ejecta was cleaned by *City Care* during this time period and from this volume, 74,528 t was cleaned off from the roads and 5,984 t was underground ejecta.

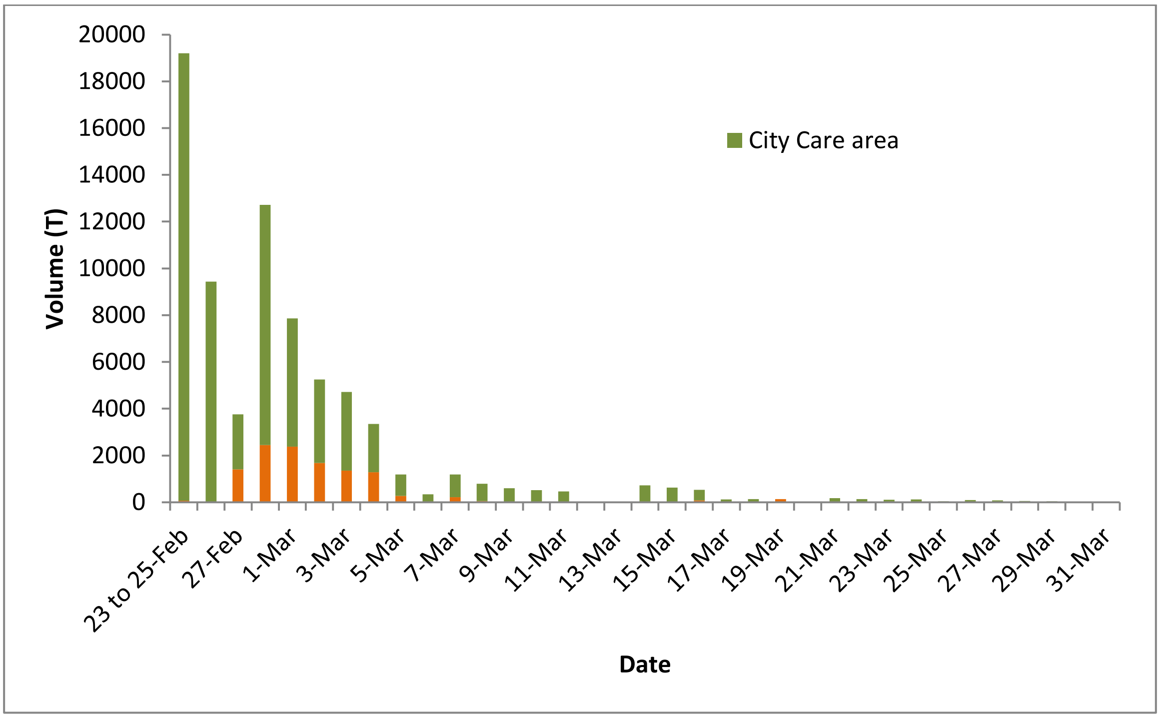


FIGURE 28: CITY CARE LIQUEFACTION EJECTA CLEAN-UP DAILY SUMMARY FOR THE MONTH OF MARCH 2011.

4.3.4.2.2. Analysis

The total values for the data was split in five volume categories. The map representing those five categories is presented in Figure 29 and Table 23 present the number of suburbs located within each volume category. From this data, there was no value located between 5,000 – 10,000 tonnes and the volume intensity decrease away from the Avon River.

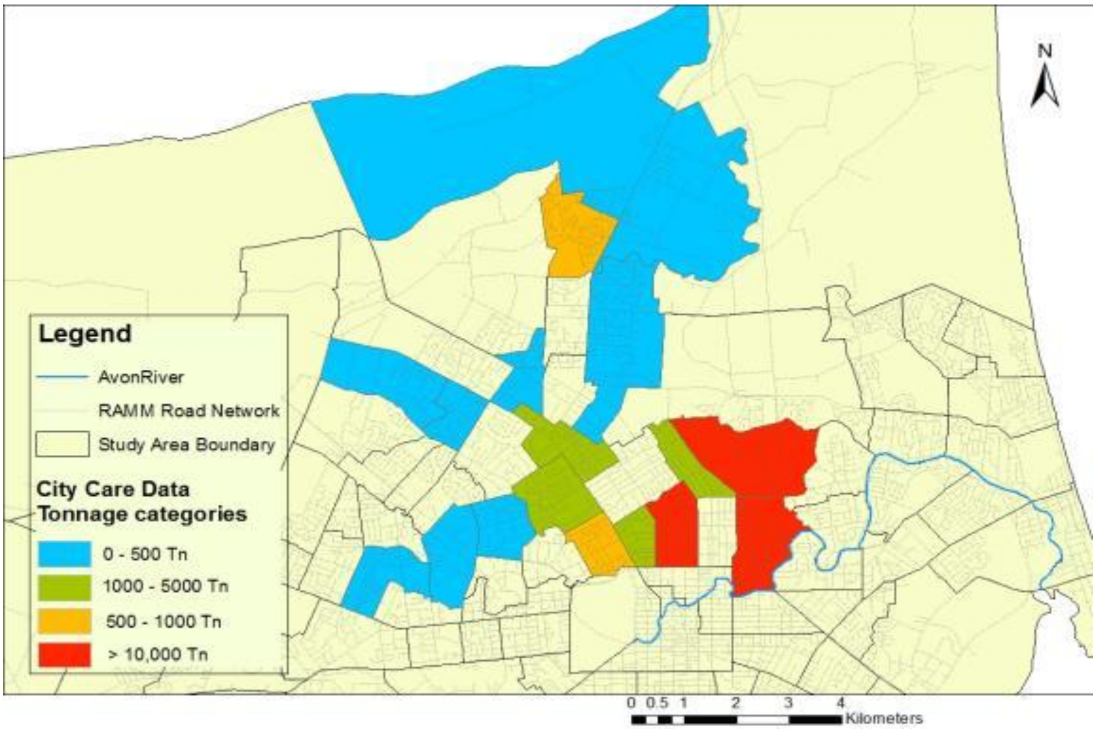


FIGURE 29: CITY CARE TOTAL CLEAN-UP ACTIVITY BASED ON VOLUME FOLLOWING THE CHRISTCHURCH 1 EARTHQUAKE (23RD FEBRUARY – 31ST OF MARCH 2011)

TABLE 23: NUMBER OF SUBURBS LOCATED IN EACH VOLUME CATEGORY

Categories	Numbers of suburbs
0 – 500 t	8
500 – 1000 t	2
1000 – 5000 t	4
5000 – 10,000 t	0
> 10,000 t	3

4.3.5. Spatial Evolution of the Clean-up Through Time

The geospatial analysis was conducted to illustrate the evolution of the clean-up cost and road clearances in space and time. This data is useful for future planning and response as it presents the distribution of costs and activities of a fine grained clean-up which could be transposed to other similar clearance responses. The geospatial results (temporal and spatial distribution analysis) of the cost and resources reflected the priority decision made by the contractor roading management team.

In order to evaluate the spatial evolution of the clean-up through time for each earthquake, the data had to be filtered by street per day. The data was then grouped into weeks following the earthquakes to calculate the cost as well as the repetition of cleaning for each street per week (see Appendix L, for the date included in each week). The resulting values were joined in ArcGIS with the RAMM road data. The costs and the amount of time that roads were repetitively cleaned (repetition) were grouped into categories to produce geospatial maps of the clean-up evolution. A cumulative map of the whole clean-up period and 16 weekly maps have been produced for both the costs and the repetition distribution following each liquefaction ejecta producing event (38 maps in total). This allowed the study of the spatial and temporal evolution of the resources following each liquefaction event. From this, it is possible to retrace the story of each earthquake and compare them.

This section will first present the percentage of road network that was impacted following each liquefaction ejecta event, followed by the spatial analysis of clean-up costs and road repetition. The results are only composed of data from the zones that Fulton and Hogan were responsible for and there are no similar data for the northern parts of the city.

4.3.5.1. Road Network Impacts

The percentage of the Christchurch road city network impacted following each event is presented in Table 24. This was calculated using the total length of road within the network as well as the length of road affected within the network for each earthquake. From those statistics, the percentages of the road network impacted following the

Darfield and Christchurch 2 earthquakes were similar and were more than double that following the Christchurch 1 earthquake.

TABLE 24: CHRISTCHURCH IMPACTED ROAD NETWORK SUMMARY FOLLOWING EACH LIQUEFACTION EJECTA EJECTA PRODUCING EVENT

	Darfield	Christchurch 1	Christchurch 2
Total length of the RAMM road network	1 904 km		
Length of the RAMM road network within Fulton and Hogan zone	1 275 km		
Length of the RAMM road network cleaned	181 km	418 km	186 km
Percentage of the whole network cleaned	9 %	22 %	10 %
Percentage of the Fulton and Hogan network cleaned	14 %	33 %	13 %

4.3.5.2. Spatial and Temporal Evolution of the liquefaction ejecta Clean-up

This section presents the spatial and temporal distribution of the liquefaction ejecta clean-up in Christchurch 2010-211 earthquake sequence (clean-up). This was done to illustrate the clean-up evolution by observing the cost and the road cleaned-up over time and space. The total clean-up cost distribution over the city for each liquefaction ejecta clean-up is presented in Figure 31 and the total road clean-up repetition is presented in Figure 32.

The evolution of the clean-up cost per street is represented by weekly maps (Week 1-4 in Figure 32 and week 5-16 Appendix M). The road clean-up evolution is presented by the numbers of road cleaned per week (Figure 34) and the amount of time the roads were cleaned during the week (repetition) and are presented by weekly maps (Week 1-4 in Figure 35 and week 5-16 in Appendix M). Because the data is presented in weekly increments, a repetition of seven times or more represent at least one job for each day of the week on that single road segment.

The geospatial distribution of the *City Care* ejecta clean-up was analysed on a weekly basis to complete the Fulton ad Hogan spatial and temporal clean-up distribution analysis. Volume categories were created to illustrate the volumes cleaned from each suburb. Figure 33 present the weekly maps of the volume cleaned by *City Care* following the Christchurch 1 earthquake as well as the area cleaned by *Fulton & Hogan*. From this it is possible to observe that large volumes of liquefaction ejecta were cleaned from the suburbs during the first 2 weeks. Week 3 clean-up was moderate with still volume cleaned within the 500 – 1,000 t category. Week 4 and 5 present a low level of intensity but is still located within highly affected area around the Avon River. This data is similar to the weekly cost repartition from the RAMM data spatial analysis where most of the efforts were concentrated within the first three weeks.

A general observation from the weekly analysis showed that the second week (week 2) following the Darfield and the Christchurch 1 clean-up periods were the most intensive while it was the first week (week 1) for Christchurch 2 clean-up period. Also, there is a greater variation in presence (activity) for the Christchurch 1 clean-up while there is a more constant presence for the two other clean-ups.

The volume of liquefaction ejecta is related to the intensity of the impacts on the road segment. The clean-up activities and associated costs for a single road segment are assumed to be proportional to the road impact intensity, thus to the volume of sediment. Rough values given from the Christchurch city contractors show that the clean-up costs are proportional to the volume of sediments (correlates at 98%, Appendix J.2). Rough tonnages and costs distribution are presented in Table 26 with an average cost/ton for each clean-up period for *Fulton & Hogan* activities. It was not possible to further evaluate this assumption due to the limited available data on volumes cleaned during each event.

TABLE 25: NUMBER OF ROADS CLEANED IN CHRISTCHURCH PER WEEK FOLLOWING EACH LIQUEFACTION EJECTA EVENT

Event	**Darfield**	**Christchurch 1**	**Christchurch 2**
	Number of roads cleaned per week		
Week 1	64	168	103
Week 2	45	338	77
Week 3	22	230	64
Week 4	93	87	41
Week 5	54	74	19
Week 6	49	43	5
Week 7	19	30	19
Week 8	18	17	35
Week 9	17	13	24
Week 10	5	14	4
Week 11	11	12	9
Week 12	7	3	6
Week 13	9	3	4
Week 14	4	6	4
Week 15	0	1	6
Week 16	4	2	2
Total	176	507	238

TABLE 26: TONNAGE DISTRIBUTION AND COSTS FOR EACH EARTHQUAKE

Clean-up period	**Tonnage**	**Cost**	**Cost/tonne**
Sept 2010 - Feb 2011	31 000 t	$NZ 1, 669,947	$NZ 53.87
Feb - June 2011	315 655 t	$NZ 7, 585,749	$NZ 24.03
June - Dec 2011	85 390 t	$NZ 2, 850,140	$NZ 33.38
Total	**533 415 t**	**$NZ 12, 105,837**	**$NZ 22.69**

4.3.5.3. Repetition of Road Clean-up

The percentage of roads cleaned in each repetition categories used to create the distribution maps was calculated related to the total affected roads for each event (Table 38). Looking at relative percentages of roads values allow to compare the events regardless of the volume difference between them. There is an evident trends showing that as clean-up advance, less road clean-up repetition occurs. Therefore, it can be expected that after five weeks, less than five additional cleaning to the same roads should be required and only once after nine weeks. There are some rare exceptions such as the Christchurch 1 clean-up's week 14 with a higher percentage of 6-10 additional cleanings. The Darfield event shows higher percentage of additional cleaning in the later stage of the clean-up (week 4 and 6) with 7 % for more than 10 repetitions compared to 4-5 % for Christchurch 2 and Christchurch 1 clean-up respectively.

There is a general trend for the total cleaning repetition of each events showing that about 40-45 % of roads were cleaned 1 time or 2-5 times, about 10 % were cleaned 6-10 times, about 5 % were cleaned 10-20 times and less than 2 % were cleaned more than 20 times (Table 27). Maps of the regions allocated to each repetition category illustrate the areas where the clean-up was concentrated (Figure 36). The regions that were repetitively cleaned are located within heavily impacted areas and represent major or important roads within those areas (Appendix N).

The small percentage of repetition located in the >20 categories for the Christchurch 1 clean-up could reflect a more efficient clean-up because of the experience gained from the Darfield clean-up, but high degree of repetition are present in Christchurch 2, when the volume and the exposure of sediment was smaller. In general, there was slightly more repetition in Darfield then during the other events. Possible reasons for multiple cleaning of roads during the clean-up of the Canterbury sequence are identified below but the results suggest that the repetition of road clean-up is a reality and needs to be considered in future clean-up management planning. Reasons are for Darfield the lack of preparedness, for Christchurch 1 the larger scale of the event and for Christchurch 2 the volunteer fatigue as well as an improved reporting habit.

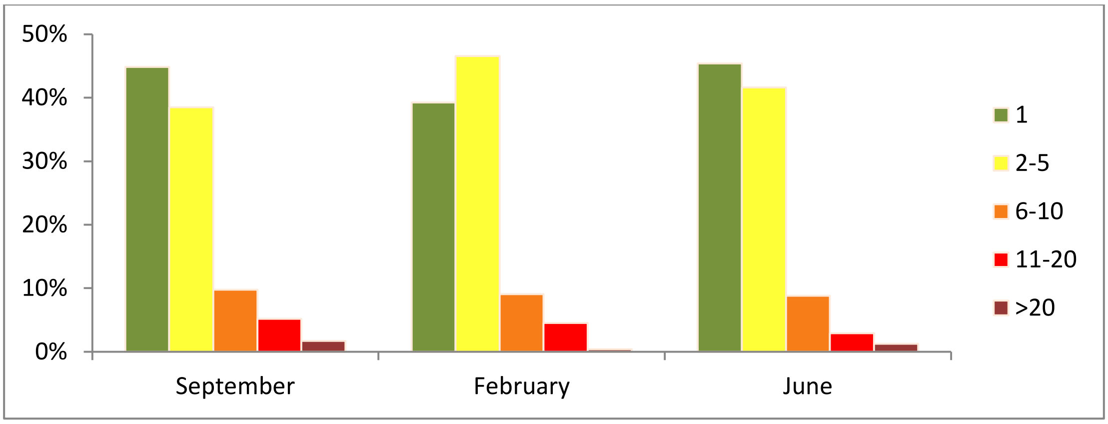


Figure 30: Distribution of the clean-up road repetition percentage for each event

Table 27: Percentage of roads cleaned for each repetition categories related to the total affected roads for each event

	1			2-5			6-10			11-20			>20		
	S	F	J	S	F	J	S	F	J	S	F	J	S	F	J
Total	45	39	45	39	47	42	10	9	9	5	5	3	2	0.4	1
Week 1	60	51	57	38	49	41	2		2						
Week 2	80	58	58	20	41	42		1							
Week 3	91	66	72	9	33	28		1							
Week 4	65	64	59	31	34	41	3	1		1					
Week 5	72	65	63	25	32	37	4								
Week 6	47	70	80	51	30	20				2					
Week 7	95	80	95	5	20	5									
Week 8	94	88	71	6	12	29									
Week 9	88	77	75	13	23	25									
Week 10	100	82	100		18										
Week 11	100	67	67		33	33									
Week 12	100	33	100		67										
Week 13	75	67	100	25	33										
Week 14	67	83	75	33		25		17							
Week 15		100	83			17									
Week 16	100	50	100		50										

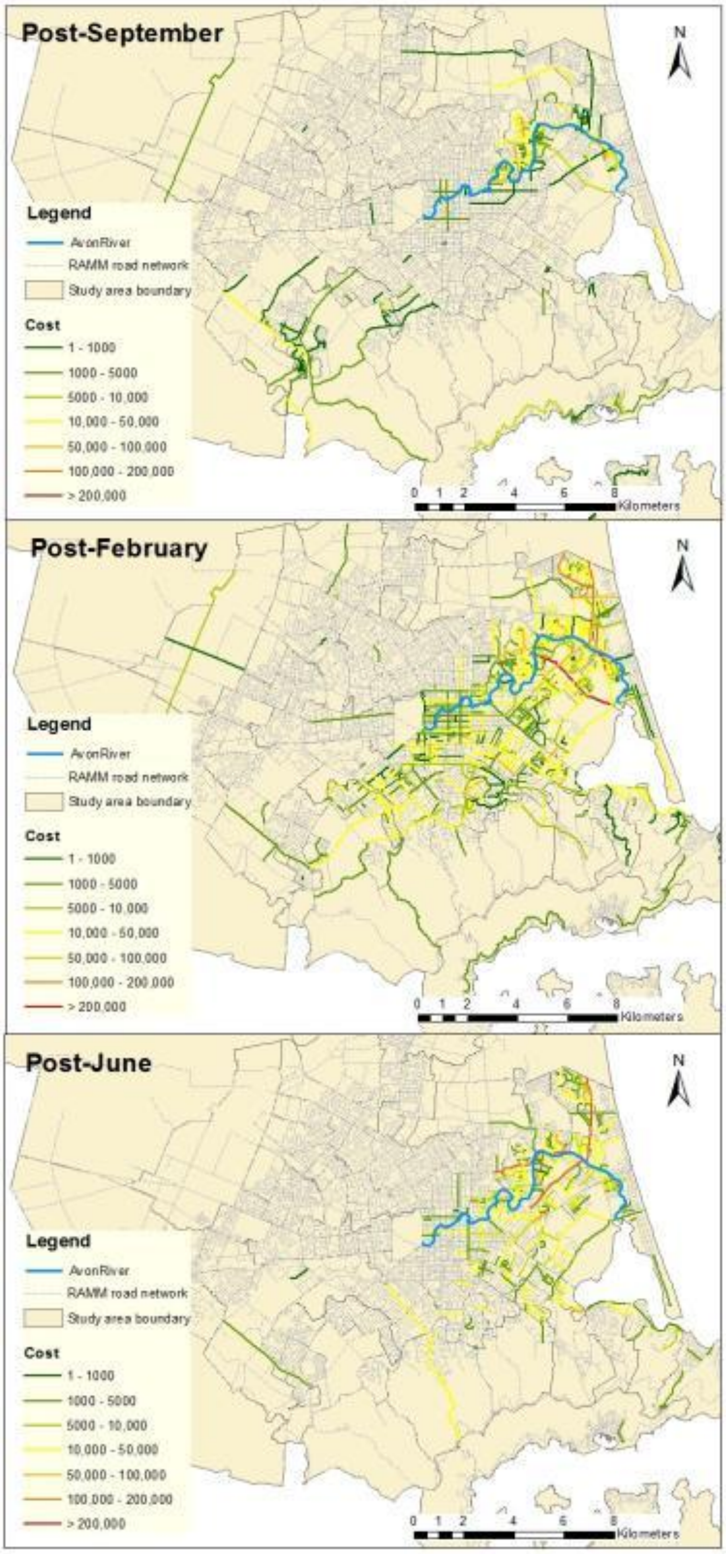


FIGURE 31: TOTAL COST DISTRIBUTION MAPS FOR THE THREE MAJOR EARTHQUAKES FOR THE THREE MAJOR EARTHQUAKES LIQUEFACTION EJECTA CLEAN-UP

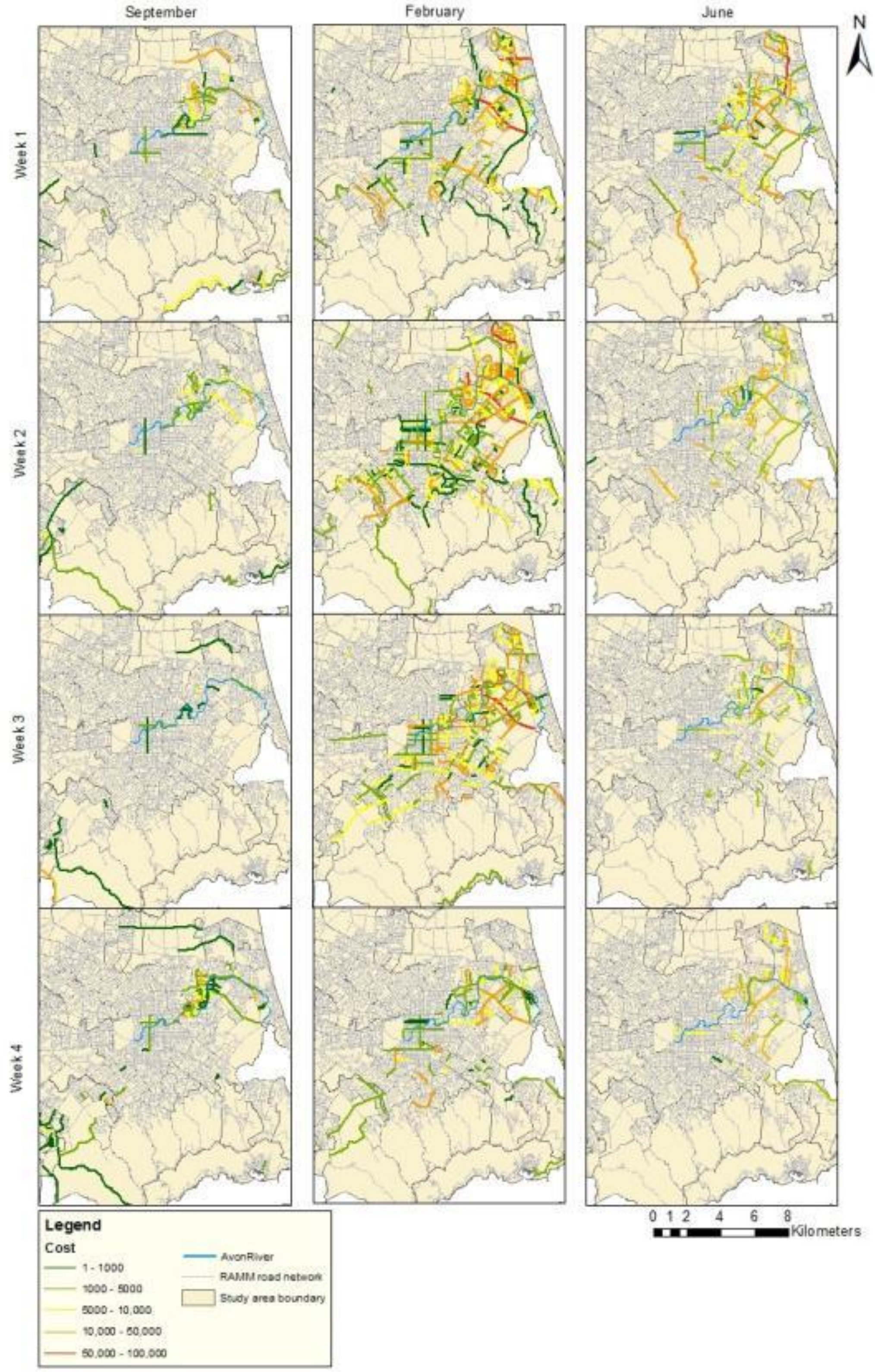


FIGURE 32: WEEKLY COST DISTRIBUTION FOR THE THREE MAJOR EARTHQUAKES LIQUEFACTION EJECTA CLEAN-UP (WEEK 1-4)

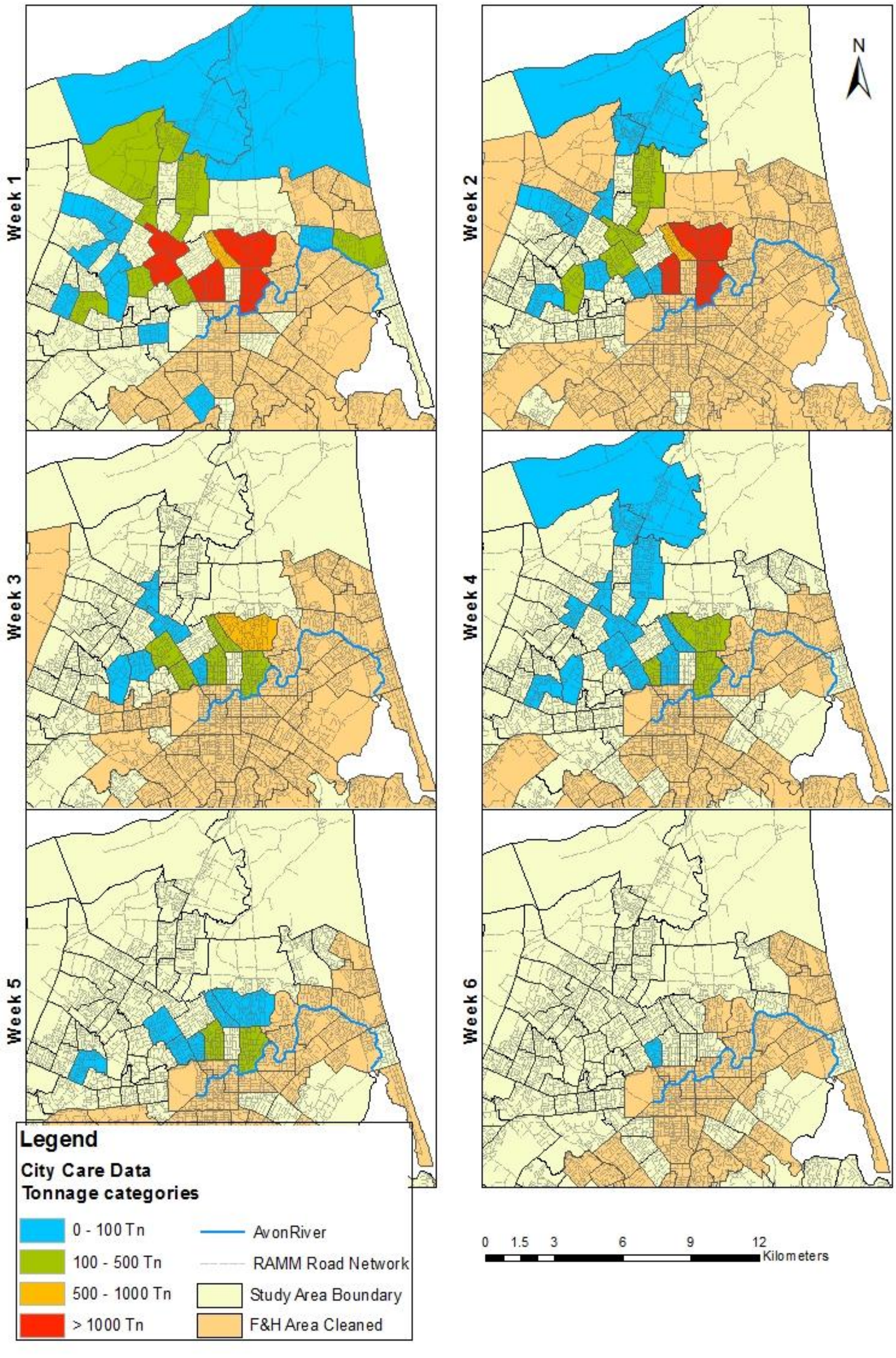


FIGURE 33: CITY CARE WEEKLY CLEAN-UP ACTIVITY OVER TIME BASED ON VOLUME CLEANED OVER THE FULTON AND HOGAN CLEANED AREAS

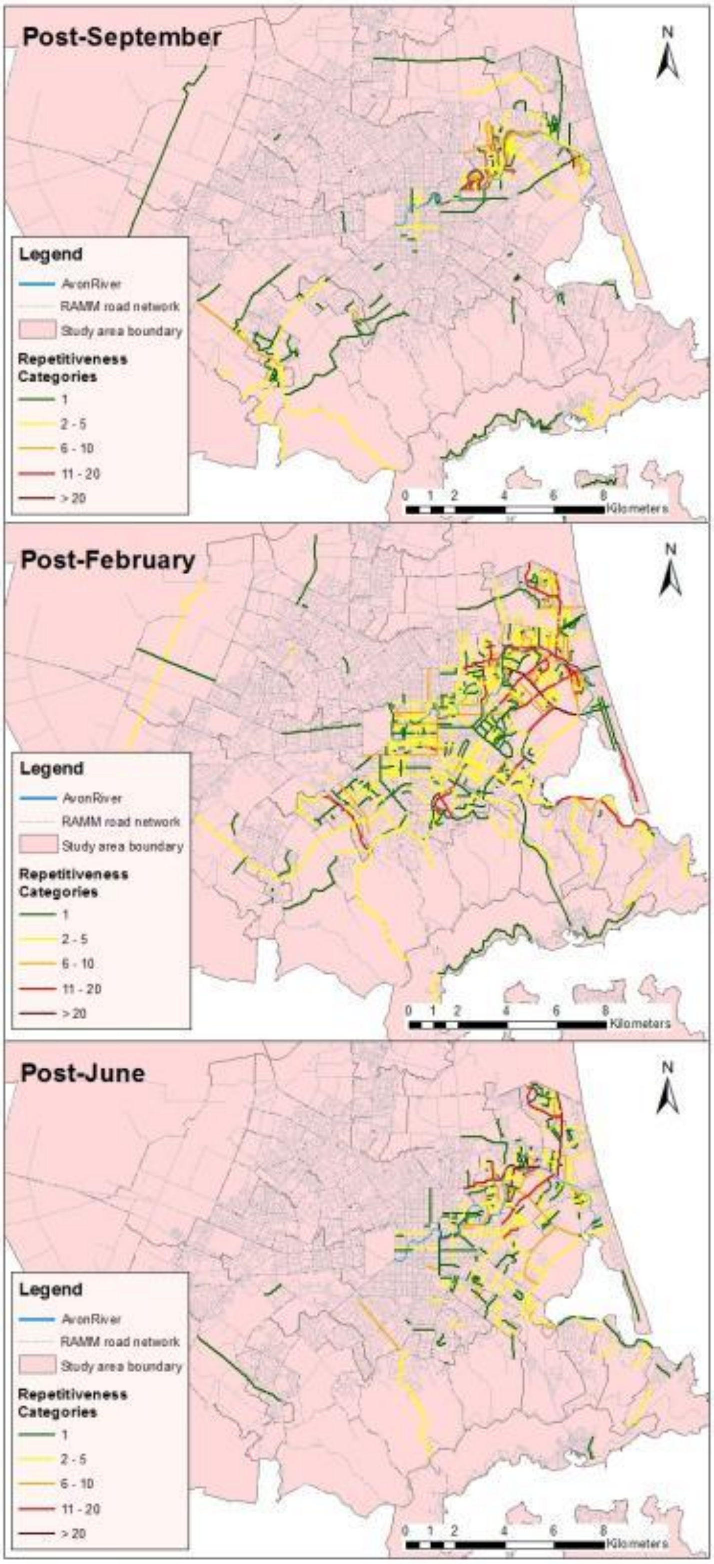


Figure 34: Total repetition distribution maps for the three major earthquakes liquefaction ejecta clean-up

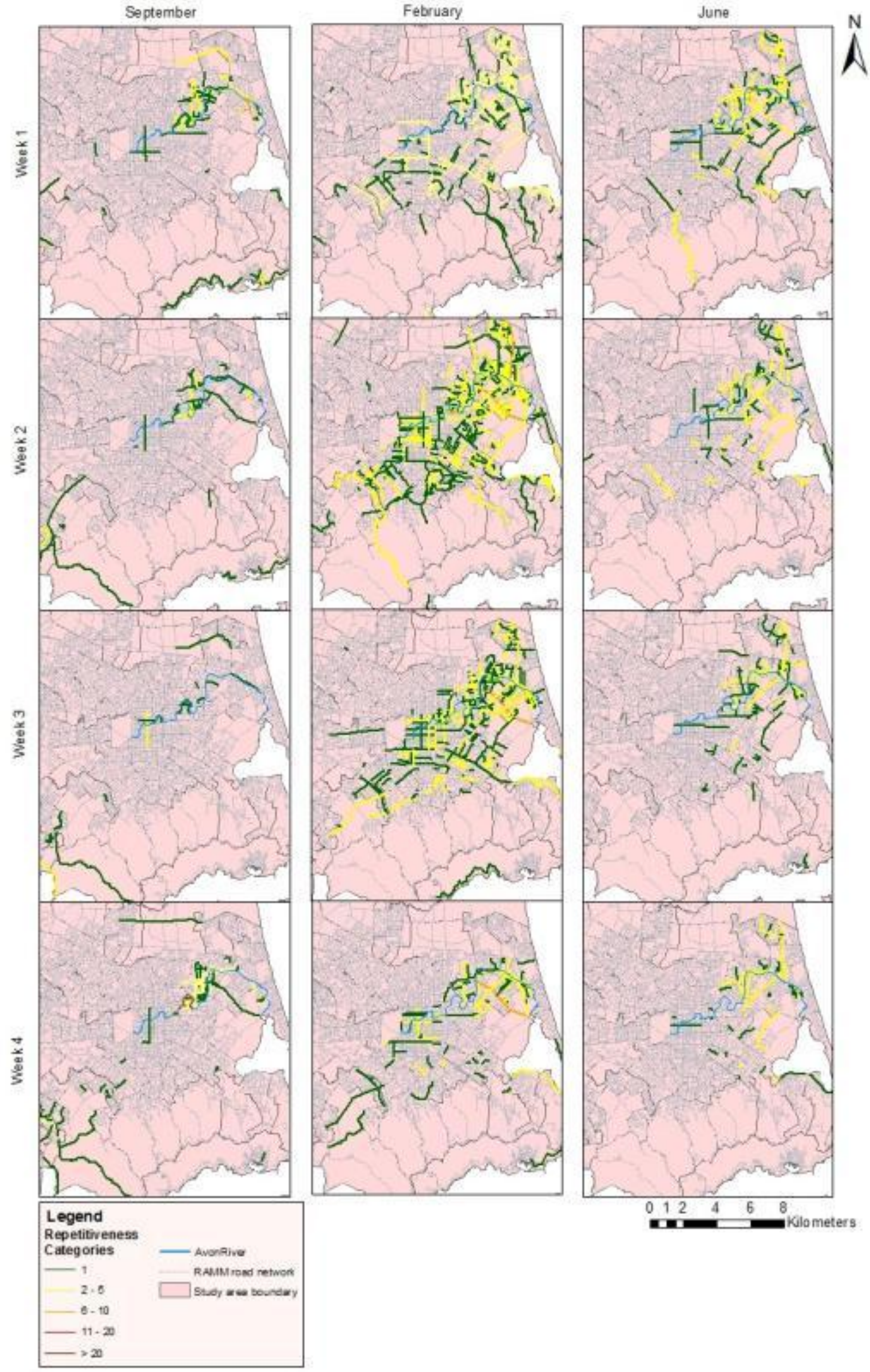


FIGURE 35: WEEKLY REPETITION DISTRIBUTION MAPS FOR THE THREE MAJOR EARTHQUAKES LIQUEFACTION EJECTA CLEAN-UP (WEEK 1-4)

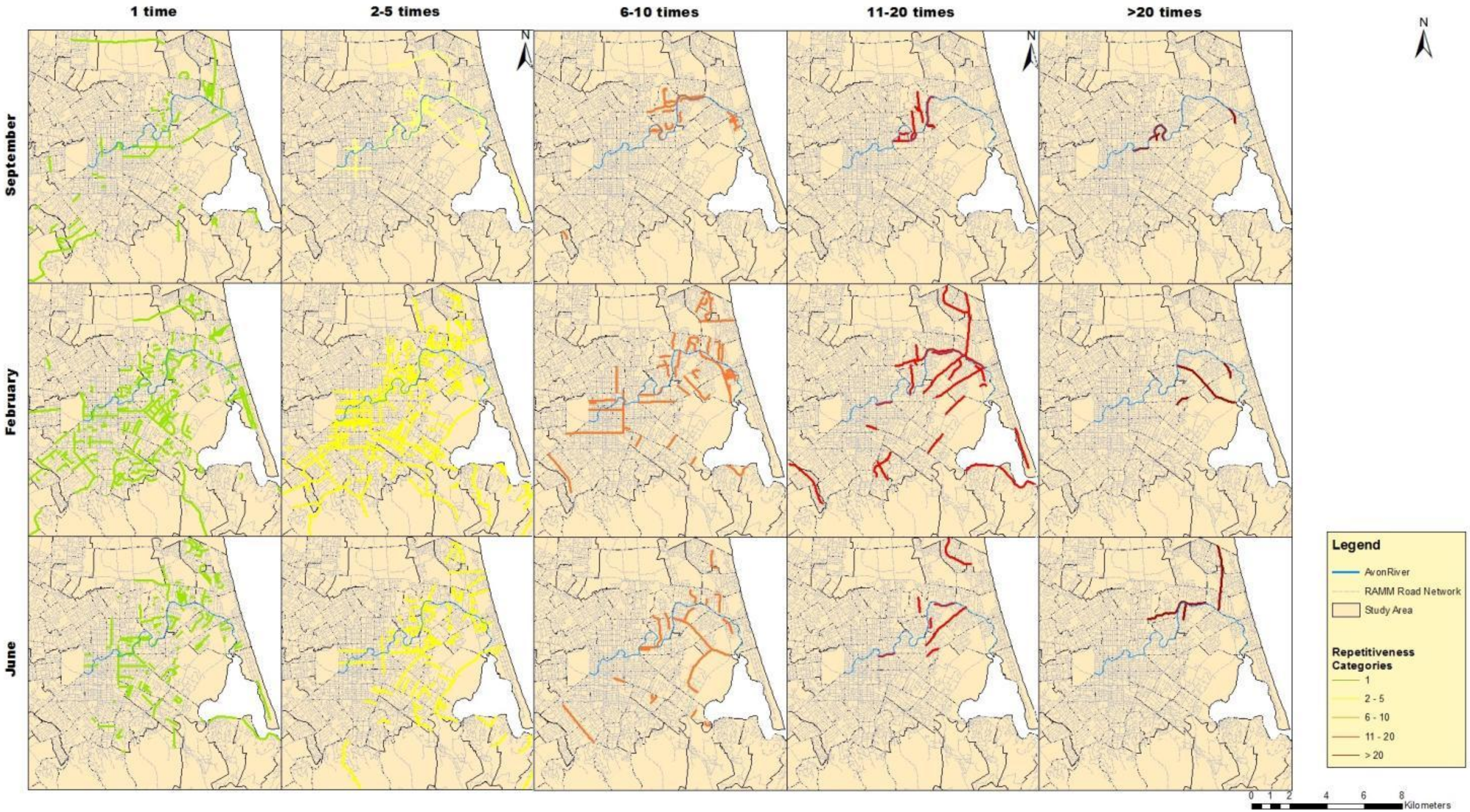


FIGURE 36: MAPS OF THE ROADS ALLOCATED FOR EACH REPETITION CATEGORY FOR THE THREE MAJOR EARTHQUAKES LIQUEFACTION EJECTA CLEAN-UP

4.4. Limitations

Because of the quality, distribution and the quantity of the data, some analysis could not be done. Knowing the level at which the streets were affected would have been useful to counteract this problem.

The detailed values or the RAMM dataset were only offered by Fulton & Hogan, fortunately, their work covered a large section of the city and reflected the most impacted areas. But there is still a large section of the city with no information. Thus, because of this missing data, the values presented here are considered as a minimum costs.

At this stage there were no hazard intensity categories for the roads of Christchurch as the T&T/ EQC land damage map only consider properties. Interpretation from the aerial photographs taken following the Darfield and Christchurch 1 earthquake for road impact would have been useful to produce cost per kilometers analysis. The time limit constrained us to produce our own photo-interpretation.

There was limited information concerning detailed data for the volumes cleaned-up per day. Only a small snapshot of data was available for us and only a small case study was able to be done. The data only include surface clean-up and do not include underground nor water clean-up that may have been contaminated with liquefaction ejecta. Those would have been a great proportion of the clean-up cost.

Tonnages of liquefaction removed were quite a challenge to work with. There was a small amount of data and the data was offered in different level of details. There was only a snapshot of eight days in early March that was shared with us from *Fulton and Hogan* zones. More tonnage was captured from the main note columns for the month of March, but this data is only minimal information. This data was offering a tonnage value on a particular street for the day. City Care offered six weeks of data, but this data was more generalised and was presented in tonnages per day per suburbs. Those suburbs were assumed to be delimited by the official city boundaries.

The machineries had a minimum renting cost of a certain amount of hours. This could have an effect on the total hours that were really put in the clean-up, but it does not affect the overall cost as those processes would occur in other disaster situation. Because of this, a labour hour component had to be included for the worker not on a machine. The best way to reflect the real working time per day was to use the total hours without material and water data.

In conclusion, the data retrieved from the contractors during the clean-up of Christchurch was typical to post disaster data; it was collected rapidly as a secondary priority by multiple people. It did not offer all the information necessary for an academic purpose, but it contained the best data available for the moment. It also offered detailed information from a recent fine grained sediment (< 1 mm) clean-up in a modern urban environment, contributing to the literature. The encounter of these limitations gave the idea of creating a list of valuable information that could be passed by to contractors during emergency planning to create a support program that contractors can be taught to use during emergency management simulation trainings. More precise reporting of activities (carting versus collection), volumes, distances, resources, time, and costs are valuable to better understand the clean-up evolution.

4.5. Conclusion

This chapter presented different ways of interpreting the data in order to illustrate the clean-up of Christchurch following the three major earthquake induced liquefaction event. This interpretation aims to minimise the consequences of disasters and increase the efficiency of the city's response by identifying the challenges and lessons learned from past event in Christchurch. It would guide and provide support for disaster planners for the clean-up of an urban environment following widespread fine grained deposition by identifying resources, costs and time required to provide a rapid and effective recovery. Clean-up of a large urban area is complex and is dependent on multiple variables. This quantitative analysis supports the earlier interview process and confirms the story of the Christchurch liquefaction ejecta clean-up.

The RAMM data offered the possibility to capture Christchurch liquefaction clean-up story though the various resources used for the clean-up of the city. The dataset was incomplete but represents the best data available for the moment related to a real fine grained sediment (<1 mm) clean-up in a modern urban environment. Trends identified in this analysis can be applied to other urban soft sediment clean-up following a disaster with caution.

A significant finding was that half of the resources and half of the costs were reached 15 days (or two weeks) following the event. The majority of the activities following a fine grained deposition happened during the first two weeks following the event and the majority of the clean-up was finished within 60 days (two months). This section illustrated the efficiency gained from the Darfield clean-up to the Christchurch 2 clean-up. It showed that a period of three months following a fine grained deposition event was observed before reaching a low and consistent work load and that past two to three weeks, most of the intense clean-up will be done.

In summary, each event clean-up evolved differently, reflecting different demands, resource availability and cleanup management. Christchurch 1 clean-up was the largest of the three cleanup operations in terms of cost, hours and resources used reflecting the higher volume and spatial distribution of liquefaction ejecta. A general trend in behaviour was observed with a fast increase in the clean-up response a few days following the event and an exponential decay style after a few weeks (two to three) to return to background levels.

Chapter 5. Fine Grained Material Properties

5.1. Introduction

One goal of this study was to investigate how the physical properties of fine grained sediment (<1 mm) can affect the clean-up strategies based on tephra sample properties from the North Island of New Zealand. It is believed that the physical properties of the fine grained material affect the capacity of transport, storage, future use of land (where fine grained material is stored), and its potential usage. This chapter presents the results from laboratory testing on tephra samples and compares them to other values found in the literature. This section presents:

- Review of the sample origin,
- Physical and geotechnical properties analysed; density, grain size, composition and plasticity,
- Angle of repose in the context of fresh tephra removal
- Implications for tephra clean-up scenarios for the samples tested,
- Future use of tephra materials and
- Synthesis of the data

5.2. Samples Tested

New Zealand offers a wide variety of young and preserved tephras deposits that are easily accessible. With the relative lack of published analysis on the engineering properties of tephra in New Zealand, it offered a second material to characterise in a clean-up context. In order to characterise different type of volcanic tephra fall, collection of samples from the North Island of New Zealand including deposits from Taupo (A.D. 186), Tawarera (Kaharoa (A.D. 1310) and Rotomahana (A.D. 1886)), Tongariro (Poutu lapilli (c. 11 000 yr B.P.)), Ruapehu and Maungataketake were required (Table 28).

None of the samples collected were fresh, however, they are considered relatively young (ranges from AD 185-1886 with an older c. 11 000 yr BP). Freshly deposited fine grained sediment (<1 mm) would be collected in a period of days to weeks following a disaster (refer to chapters 3 and 4). Some properties, such as the compaction and the level of weathering from the samples collected, will differ to freshly fallen material.

Three general magma compositions, basaltic, andesitic and rhyolitic were used as end members to determine the impact of different eruptions. Effects from different eruption style such as wet and dry were included in the study (Table 5.1). It was also considered that grain size and thickness of a deposit decrease with distance to the source (Houghton et al. 2000).

5.2.1. New Zealand Eruptions Sampled

Samples from young eruptions of different composition were collected from the Taupo Volcanic Zone and from the Auckland Volcanic field in the North Island of New Zealand. The eruptions were chosen because of their young age, their good preservation and their accessibility for sampling. This section presents a summary of the sampled eruption.

5.2.1.1. Taupo Eruption AD 185

Taupo volcano is a large and highly active caldera with a magma effusion rate of 0.2 m^3s^{-1} (Wilson, 1993). It has been active for at least 300,000 years (GeoNet, 2013) and has erupted at least 28 times since the caldera forming eruption Oruanui (22 600 ^{14}C years BP) with a large variation in volume and repose periods (Wilson, 1993). The Taupo eruption is the youngest eruption from the volcano and it is considered as the most violent eruption in the world for the last 5,000 years (GeoNet, 2013). The eruption was complex and presents a variety of rhyolitic eruption styles ranging from dry fall to wet phreatomagmatic and from pyroclastic flow to caldera formation. Its deposits are found all across the central North Island with well preserved and easy to access outcrop.

The Taupo eruption started with small phreatomagmatic activity producing the initial ash (Y1) (Appendix S). It was followed by the Hatepe plinian dry vent eruption (Y2) and the Hatepe phreatoplinian ash phase (Y3) in response to a large amount of water entering the vent. A break in time is represented by gully erosion between subunit 3 and 4. Phreatoplinian activity started again with the deposition of the Rotongaio ash (Y4) followed by another dry phase of the Taupo plinian (Y5) and the powerful Taupo ultra-plinian eruption and ignimbrite deposition (Y6-Y7) (Walker 1981 and Wilson, 1995). Unit 2, 3, 4 and 5 were sample from a road cut along Highway 5 (Figure 37).

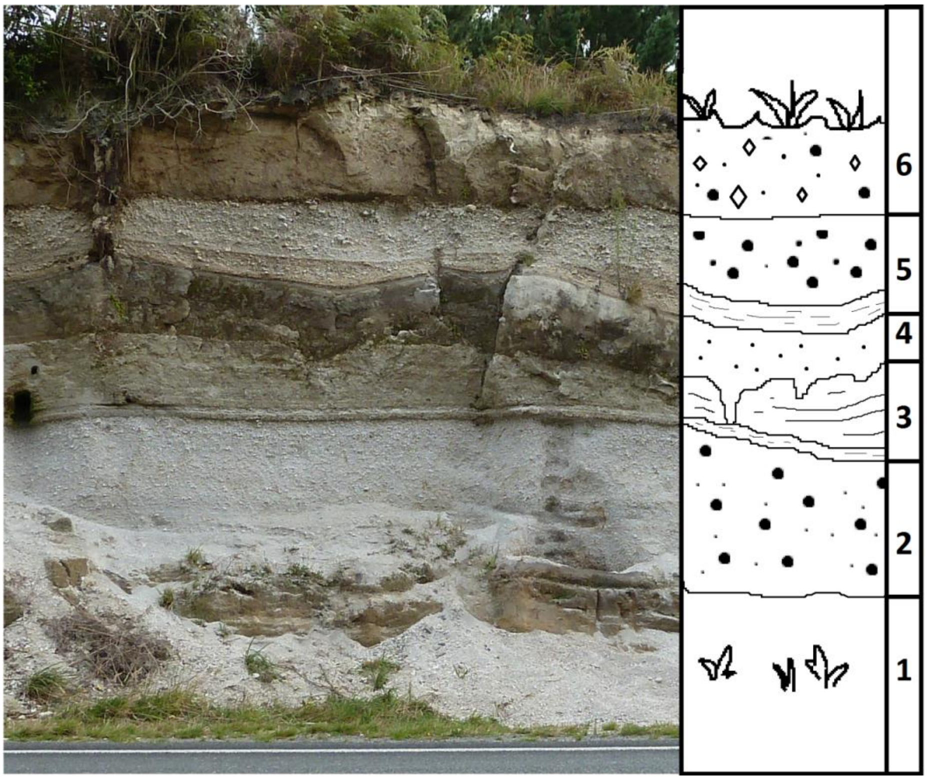


FIGURE 37: TAUPO ERUPTION CROSS-SECTION, HEIGHT OF THE OUTCROP IS ABOUT 4.6M. UNIT 2, 3, 4 AND 5 WERE SAMPLES LOCATION: HIGHWAY 5, E2788151/N6267950.

Table 28: Eruption description sampled for each magma composition and summary of the results

Composition	Volcano	Eruption style	Deposit	Mean density (kg/m^3)			Clay mineral content
				Wet	In-Situ	Dry	
Basaltic	Tawarera	Plinian fall	AD 1886		1025	872	Yes
	Maungataketake	Base surge and tephra fall		1836 2080	1381 1938	1811 1532	Yes
Andesitic	Tongariro	Fall	Poutu lapilli (Hitchcook & Cole, 2007)		1180	964	N/A
	Ruapehu	Fall			1358	1119	N/A
Rhyolitic	Taupo	Magmatic	Unit 2 (Hatepe Plinian) Unit 5 (Taupo Plinian)		745 1072	506 776	N/A N/A
		Phreatoplinian	Unit 3 (Hatepe) Unit 4 (Rotongaio)		1150 1582	840 1338	Present No
	Tawarera	Mud fall	Rotomahana AD 1886		1279	985	Yes
		Plinian fall	Kaharoa		1268	1051	N/A

5.2.1.2. Kaharoa AD 1310 Eruption (Tawarera)

The Kaharoa eruption was a large plinian eruption that occurred less than 100 years ago, AD 1310. It is considered by Nairn (2002) to be the largest eruptive episode in New Zealand during the last 1000 years with volumes larger than 5 km^3 of pyroclastics and 2.5 km^3 of lava. It is the youngest rhyolitic eruption from the Tawarera Centre and samples were taken from the fall unit of the Kaharoa tephra (a fine and coarse pumice representatives) (Figure 38). Bonadonna et al (2004) used the Kaharoa scenario to assess impacts for a future rhyolitic eruption of the same scale from Tarawera in modern times.

5.2.1.3. Tawarera AD 1886 Basaltic Scoria Eruption and Rotomahana Mud Fall

The Tawarera A.D. 1886 eruption is one of the rare basaltic plinian eruptions. It occurred on the 10^{th} of June 1886 A.D and produced an eruption column of 11 km from a volcanic fissure vent on Mt. Tawarera (Nairn, 2002). The Rotomahana mud was erupted later when rising dykes reached the hydrothermally weathered rhyolitic country rock from the Lake Rotomahana. The Tawarera and Rotomahana deposit covered an area on land of c. 15 000 km^2 (measured immediately after the eruption by Smith (1886) and Thomas (1888)). The Rotomahana mud fall was deposited as surges near the vent and travelled more than 6km west. The surges blowed away nearby camps and reached two Maori villages, causing building to fail under the weight of the mud fall and killing about 108 people (Nairn, 2002).

5.2.1.4. Poutu Lapilli c. 11 000 yr BP (Tongariro)

The Poutu lapilli is part of the Mangamate Formation erupted between 11 000 – 12 000 cal. year BP from Tongariro volcano. It is the youngest deposit from this formation and is identified as PM6. It was a large subplinian andesitic eruption (VEI 4). Hitchcock & Cole (2007) describe the significant impacts of such an eruption in a present day environment.

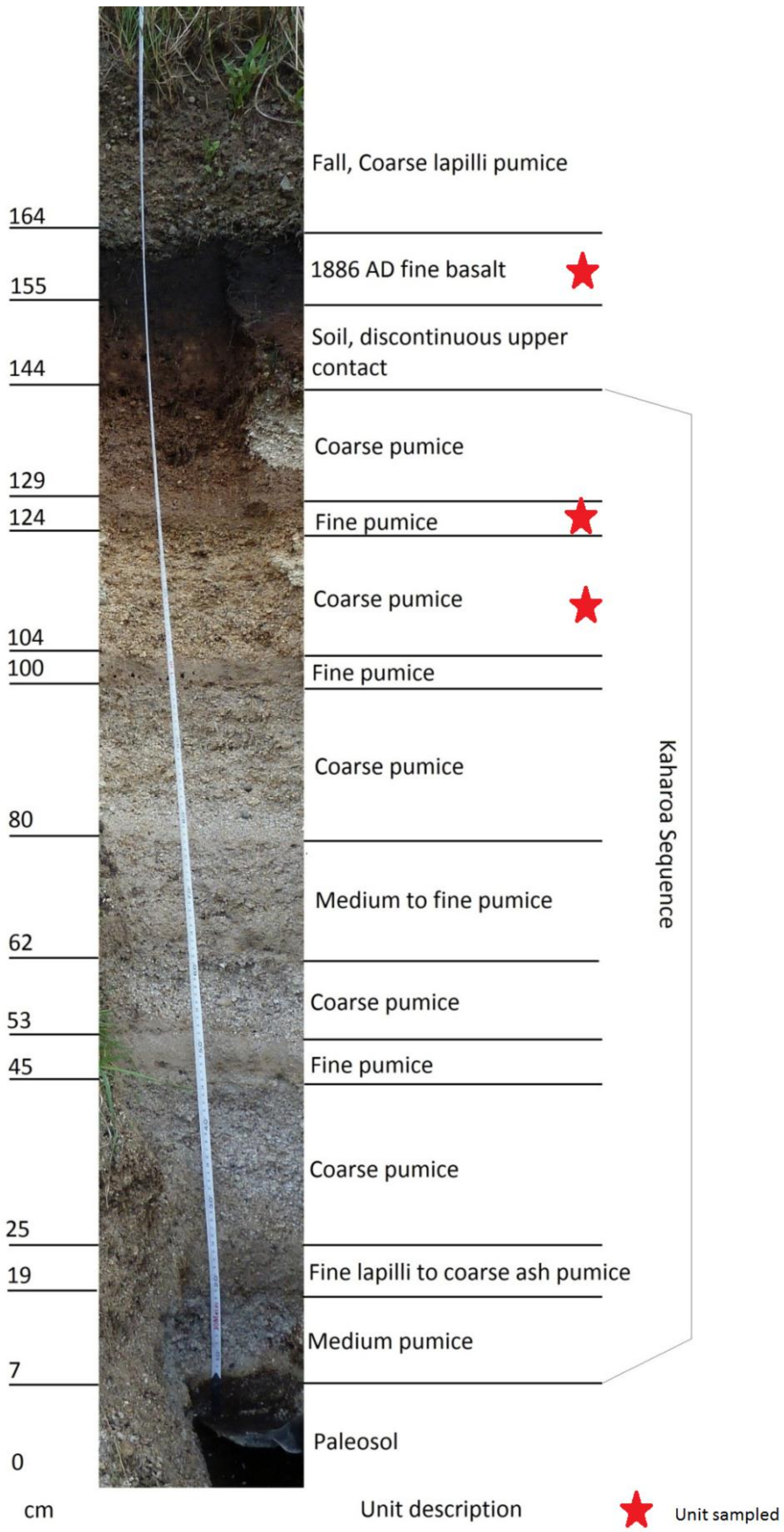


Figure 38: Kaharoa eruption sequence cross section. Location: E2818844/N6315433

5.3. Physical and Geotechnical Properties

This section aim to present the physical and geotechnical properties of the tephra samples collected from the North Island of New Zealand. It briefly presents the sampling method, an overview of the properties tested, their implications, the technique used to analyse the samples and the results. The properties tested are:

- Density
- Granulometry
- Composition and plasticity
- Angle of repose

5.3.1. Tephra Sampling

Technique used to acquire and store the tephra samples were based on Lewis and McConchie's Analytical Sedimentology reference book (1997). Undisturbed samples (as lowly compacted or loosened as possible) were collected with cylinders ranging from 35.50-36.53 mm internal diameter and 158-199 mm in length were inserted through a horizontal section of the deposit with the help of a large hand piston. It was essential to preserve pore spacing between particles to understanding how tephra settle and act during cleaning. Prior to field work, cylinders were measured, weighted and tagged in the laboratory. Five samples per unit were taken from the base of the same horizon on the same section. The push tube's diameter restricted the sampling to units with thickness greater than 5 cm to avoid cross-contamination from the surrounding units, restraining sampling to proximal deposits for fine and thin units.

5.3.2. Density

The density of a material is dependent on the particle grain size, particle shape, mineralogy, vesicularity, compaction of the particles, particle density and moisture content. Large homegeneous pumiceous samples have a lower density then fine heterogeneous pumiceous samples because the fine clasts fill up more empty space between particles while the large clasts leave larger voids between particles. Additionally, heterogeneous pumiceous deposits have a lower density then a heterogeneous fine clast sample when dry (Figure 39). Compaction is affected by the particle shape and hardness (friability). Friable material, such as volcanic clasts, compacts more easily as the clasts break into finer particles during compaction. Texture, structure and organic matter such as root penetration can impact the bulk densities by changing the pore space of the samples (CSS, 2012).

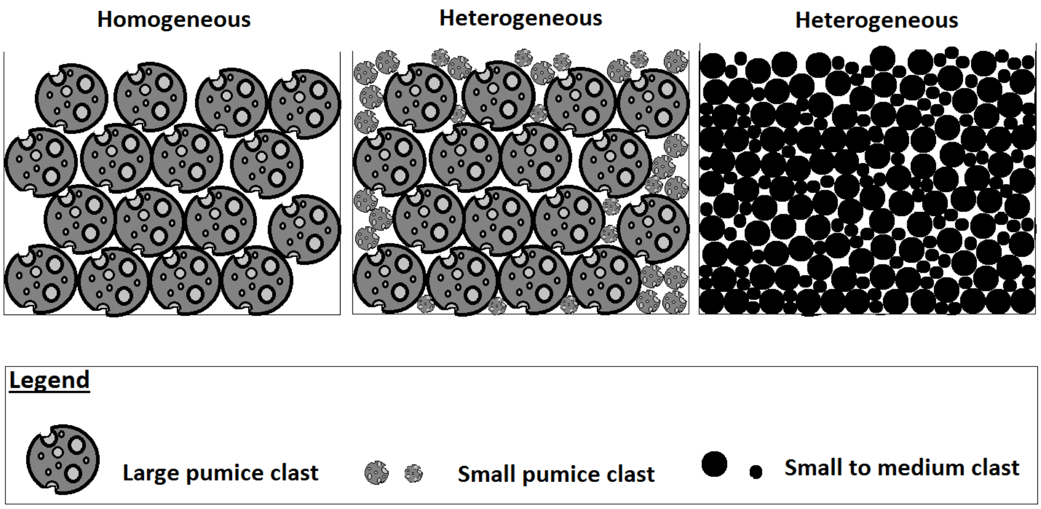


FIGURE 39: SCHEMATIC REPRESENTATION OF PARTICLES WITH DIFFERENT PROPERTIES AND THEIR IMPACT ON THE DENSITY (INCREASE IN DENSITY FROM LEFT TO RIGHT)

The purpose of measuring density was to examine the natural character of the deposits in terms of moisture content and natural compaction. Bulk samples in-situ, dry and some wet densities were measured (see Appendix P for methods). The testing technique used was based on Lewis & McConchie's (1997). Unfortunately, for the Taupo Volcanic Zone field work, the level of un-consolidation of the tephra samples prevented the tephra from staying within the cylinders to calculate the wet densities of the samples.

The locations and densities (wet, in-situ and dry) of the samples are presented in Table 29 and are compared in Figure 40. The values presented are the average of five measurements for each sample. The density results range from 498 kg/m^3 (Taupo Unit 2 Distal) to 1699 kg/m^3 with (Maungataketake fall).

The results show:

- Kaharoa rhyolitic samples are denser then the Taupo rhyolitic samples

- In general, finer grained samples are denser then coarser samples (Kaharoa fine pumice (1162 kg/m^3) versus Kaharoa coarse pumice (941 kg/m^3))

- In general, heterogeneous pumiceous deposits are less dense then heterogeneous fine clasts sample when dry; (Taupo Unit 2 (515 kg/m^3) versus Taupo Unit 4 (1338 kg/m^3)).

- The wet derived samples are generally denser (except for one of the Taupo Unit 3 distal sample which is less dense then Taupo Unit 5 distal).

- The changes between in-situ and dry densities are similar across most of the sample set (ranging between 200-400 kg/m^3).There is one exception: the 1888 coarse proximal basaltic samples with densities that varies by 10 kg/m^3 (ranging from 40-50 kg/m^3). This is represented by a similar curve gradient in Figure 40 and can be explained by better drainage in coarse grain samples than in small grain samples.

TABLE 29: LOCATIONS AND DENSITIES (WET, IN-SITU AND DRY) OF THE SAMPLES

Unit	Location		Average density		
	E	N	Wet	In-Situ	Dry
			kg/m3		
TAUPO UNIT 2 PROXIMAL	2788151	6267950		749	515
TAUPO UNIT 3 PROXIMAL	2788151	6267950		1267	937
TAUPO UNIT 4 PROXIMAL	2788151	6267950		1582	1338
TAUPO UNIT 5 PROXIMAL	2788151	6267950		887	608
TAUPO UNIT 6 PROXIMAL	2813239	6245385		990	788
TAUPO UNIT 2 DISTAL	2805394	6251774		740	498
TAUPO UNIT 3 DISTAL	2809157	6249382		1242	880
TAUPO UNIT 3 DISTAL	2805394	6251774		941	704
TAUPO UNIT 5 DISTAL	2805394	6251774		1258	945
KAHAROA FINE	2818844	6315433		1409	1162
KAHAROA COARSE	2818844	6315433		1128	941
ROTOMAHANA MUD	2805956	6319806		1279	985
1886 BASALT	2805956	6319806		1059	778
1886 PROXIMAL	2817524	6319545		628	586
1886 PROXIMAL	2817524	6319545		1082	1029
1886 DISTAL BASALT	2818844	6315433		1333	1095
MAUNGATAKETAKE BASE SURGE	1755874	5903774	1836	1811	1381
MAUNGATAKETAKE FALL MIX	1756057	5903646	2076	1820	1377
MAUNGATAKETAKE FALL COARSE	1756033	5903675	2084	2057	1688
POUTU COARSE	2748227	6232406		1047	850
POUTU MEDIUM	2748227	6232406		1236	1028
POUTU FINE	2748227	6232406		1257	1013
ANDESITE	2747849	6218350		1654	1312
ANDESITE	2747849	6218350		1208	1026
ANDESITE	2747849	6218350		1329	1061
ANDESITE	2747849	6218350		1239	1076

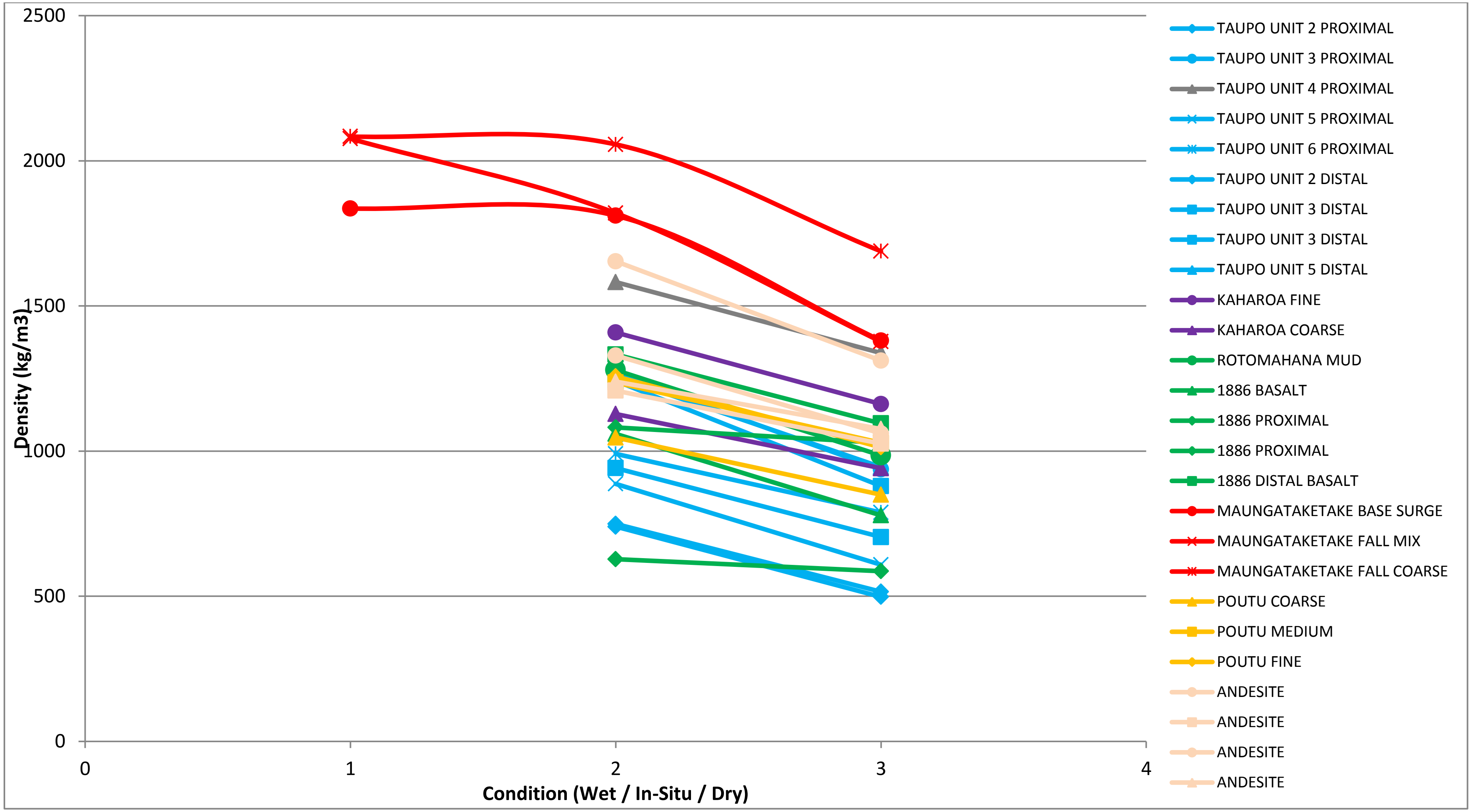


FIGURE 40: DENSITY RESULTS COMPARISON GRAPH

5.3.3. Granulometry

The thickness and maximum grain size of a volcanic fall deposit decreases exponentially from the source to medial distances (Houghton *et al.*, 2000). The height of the plume, presence of wind and wind direction all affect the fall deposition. Coarse and dense materials are unlikely to be transported up the plume but are expected to be deposited ballistically around the vent. Thus, proximal clasts are usually coarser and denser while more distal deposits are finer and less dense. The Taupo grain size distributions are compared with literature values in Appendix T.

5.3.3.1. Particle Size Analysis

Particle size is a fundamental property of sediments. It can be used to determine the material history and dynamics, from its origin through transport and deposition. Additionally, it assists in determining the likely behavior of the sample in future environment. It is important to determine the size of the tephra particles to understand its potential behaviour in various situations during a volcanic crisis. For the purpose of cleaning, grain size is important to determine the suspension, volatility and compaction capacities.

Grain size analysis was done back in the laboratory using a joint method of dry sieving and laser diffraction. Samples were prepared following the method from Lewis and McConchie (1997) which required sample disaggregation, removal of the organic matter, cleaning then drying. Details of the sample preparation are presented in an extended method (Appendix P).

Only one test was done for each sample per location for grain size analysis. Samples were first sieved at 0.5 Φ grain size intervals from -4.0 to 0.0 Φ (16 to 1 mm). The sample portion that was smaller than 0.0 Φ (<1 mm) was analysed using a Saturn Digisizer II 5205. The results from the manual sieving were recorded in weight percentage retained by the sieve and the laser sizer results were recorded as a cumulative percentage of the volume finer then a set diameter. All of the results were obtained in accordance to the NZ4402:1986 standard test method.

Particles were highly irregular and fragile requiring multiple runs through the laser sizer to increases confidence in the results. Each sample was analysed 3 times through the laser sizer with 5 runs per analysis (15 grain size analysis per sample).

The results were plotted on a particle size diameter (mm) – cumulative percentage finer graph (Figure 41, Figure 42, Figure 43 and Figure 44). Graphs were joined to facilitate comparison between different samples of the same eruption style or magma composition and are compared to the average particle size distribution of the Christchurch liquefaction ejecta data (Appendix U). Graphs represent the phreatomagmatic eruptions, rhyolitic eruptions, basaltic eruptions and andesitic eruptions.

The wet derived samples are fine grained and present a general similar trend. The Rotomahana mud is the coarsest and the Maungataketake base surge the finest. This can be explained by the presence of larger clasts in the Rotomahana mud from the simultaneous basaltic fall. The rhyolitic samples are split into three grain size distributions. There are the coarse samples (with less than 20% smaller then 1cm), the finer samples (with 60% finer then 1cm) and Taupo Unit 5 (with more than 90% of its material under 1cm (80% of its material is between 0.02-1 cm)). Andesitic samples also present a large range of grain size distribution. In general the basaltic samples are fine grained except for the 1886 proximal basaltic deposit which is coarser.

There is a gap in data at the transition between methods. The gradient of the curves between the two methods is proportional to the amount of particle located within the grain size range of 0.3-1 mm. A high gradient indicate the presence of particles within the diameter range and a low gradient indicates low to null presences. Methods are comparable despite the gap as they both represent percentage of finer particle size.

The uniformity coefficient and the median grain size were calculated and are presented in Table 30. A uniformly graded sample will have Uniformity coefficient < 5 while a well-graded samples will have a Uniformity coefficient > 5 and a Coefficient of curvature between one and three.

The results show that most of the samples have some fines components. Few grain sizes are small enough to be in the clay fraction classification. Most of the samples have their finer grain sizes in the silt fraction of the classification. When compared to the Christchurch liquefaction ejecta particle distribution, the tephra samples have a greater range of grain size.

Liquefaction sample is a well-graded sand and most of the tephra samples are well-graded sand with some coarse silt and fine gravel.

TABLE 30: TABLES OF MEDIAN GRAIN SIZE AND UNIFORMITY COEFFICIENT RESULTS

Sample	Median grain size (mm) (d50)	Uniformity coefficient (d60/d10)
Christchurch Liquefaction Ejecta	0.2	6.67
Phreatomagmatic samples		
Taupo Unit 3 Proximal	0.7	20.00
Taupo Unit 3 Distal	0.4	40.00
Taupo Unit 3 Distal	0.09	17.00
Taupo Unit 3 Distal	0.08	13.00
Taupo Unit 4	0.09	42.50
Rotomahana Mud	0.03	16.67
Maungataketake Base Surge	0.09	7.22
Basaltic samples		
1886 Basalt Proximal	4	83.33
1886 Basalt Distal	0.07	13.75
1886 Basalt Distal	0.01	1.64
Maungataketake fall	0.0035	1.03
Maungataketake fall	0.0045	2.11
Andesitic samples		
Poutu Fine	0.06	22.00
poutu Medium	0.2	35.71
poutu Coarse	1.4	150.00
andesite	1.2	150.00
andesite	3.5	2.67
andesite	0.18	10.00
andesite	0.6	8.75
Rhyolitic samples		
Taupo unit 2 Proximal	1.8	52.50
Taupo Unit 2 Proximal	2.4	37.50
Taupo Unit 5 Proximal	0.11	9.00
Taupo Unit 6 Proximal	0.15	56.00
Kaharoa Fine	0.25	125.00
Kaharoa Coarse	3.5	33.33

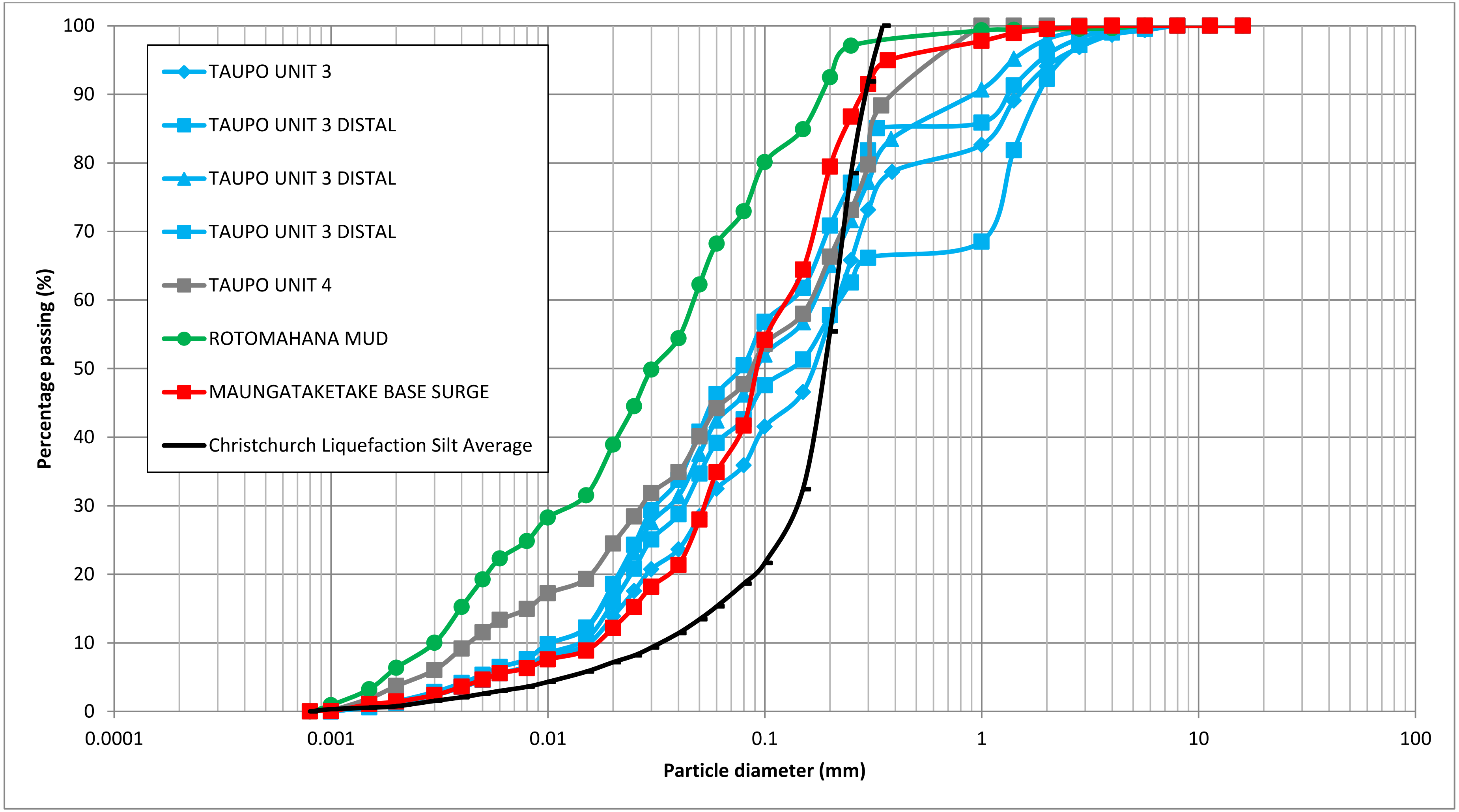


FIGURE 41: PHREATOMAGMATIC ERUPTION SAMPLES GRAIN SIZE DISTRIBUTION CHART

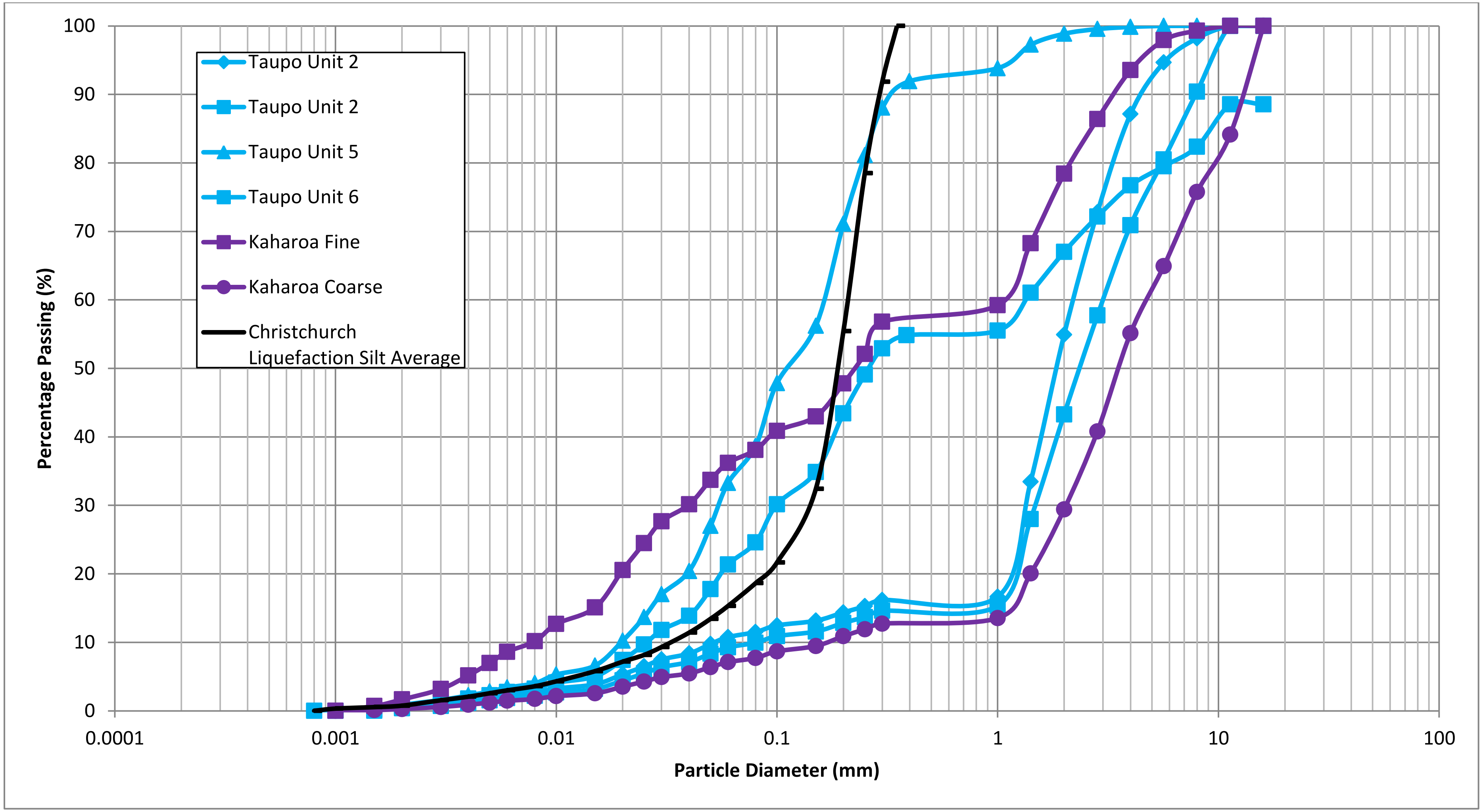


FIGURE 42: RHYOLITIC ERUPTION SAMPLES GRAIN SIZE DISTRIBUTION CHART

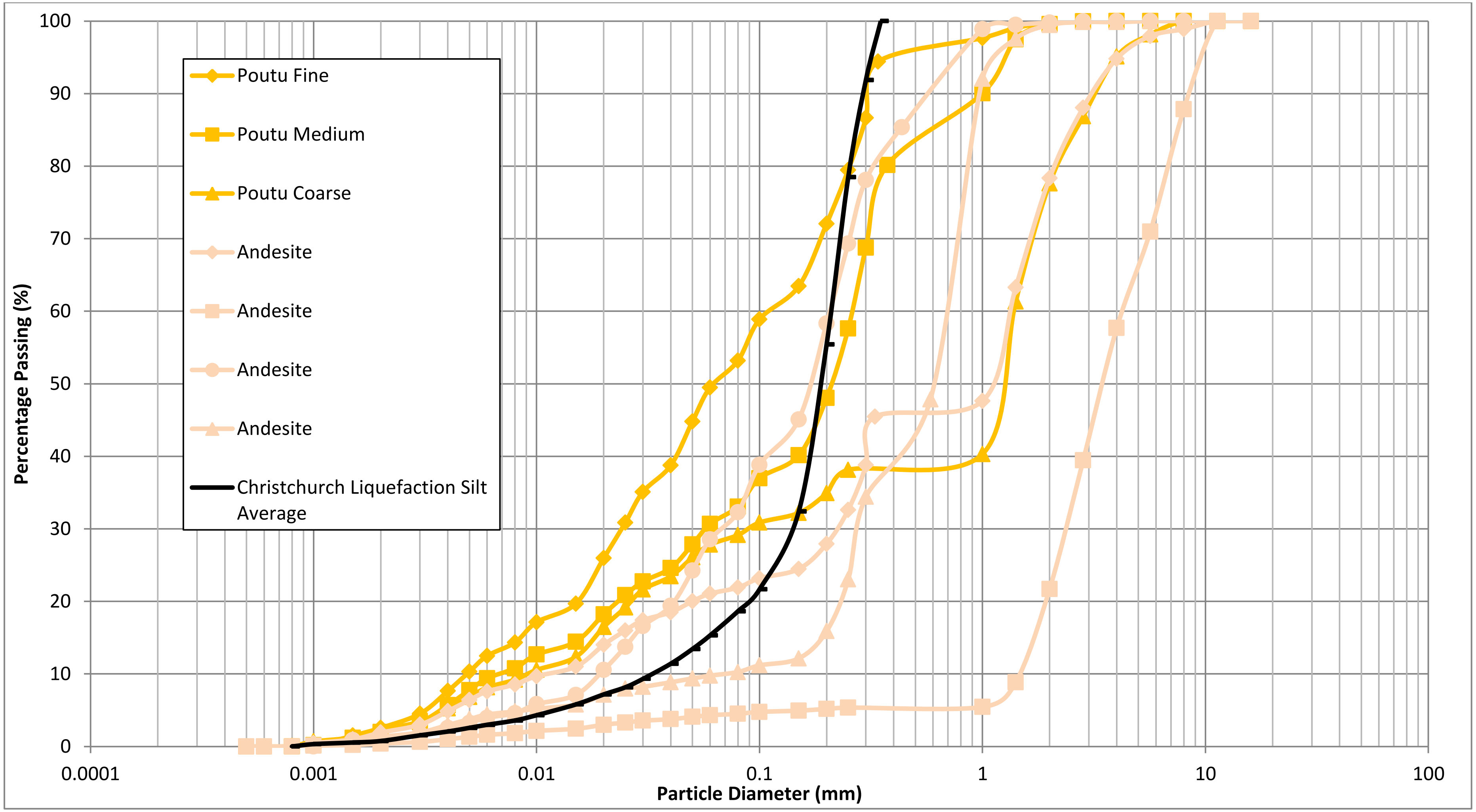


Figure 43: Andesitic eruption samples grain size distribution chart

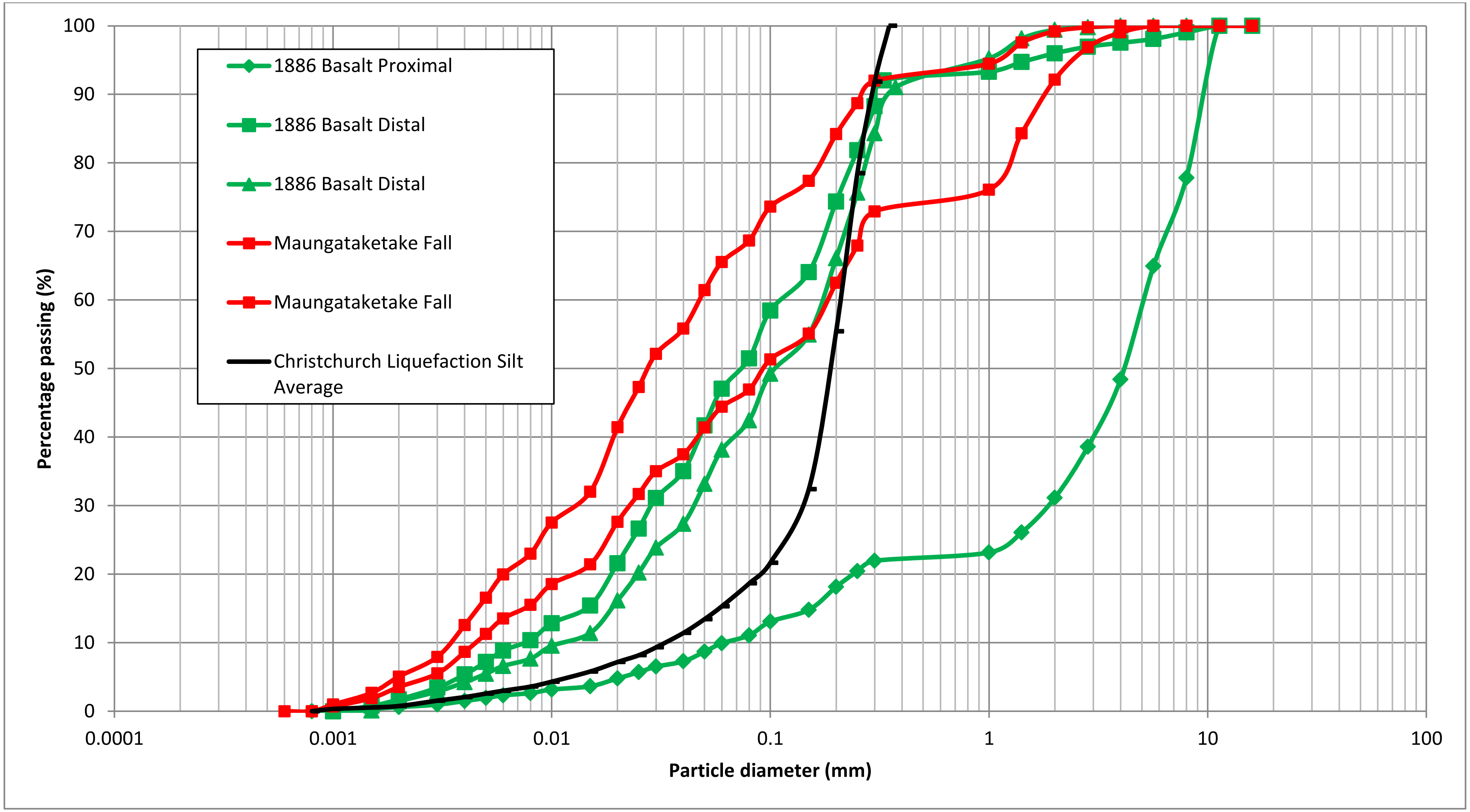


FIGURE 44: BASALTIC ERUPTION SAMPLES GRAIN SIZE DISTRIBUTION CHART

5.3.4. Composition of the Fines and Plasticity

The presence of clay can affect the sample properties and behaviour. Wesley (1973) describes that volcanic soils behave differently from the "conventional" soils. They differ in hardness and in weathering process. For example, a volcanic soil can contain allophane, a clay mineral produced by the weathering of feldspar (Allbrook, 1985). Allophane is usually the product of in-situ weathering of coarse silt to fine sand particle sized volcanic tephra (Wesley, 1973). It has been observed by Frost (1967) and Wesley (1973) that soils containing allophone clays, once oven or air dried, would behave like a non-plastic soil. The common techniques used to identify the presence of allophone clays are X-Ray diffraction (XRD) or electron microscopy (if available). If neither technique is available a classification approach can be taken based on four criteria; 1) volcanic parent material, 2) very high water content, 3) very high liquid and plastic limits lying below the A-line (Figure 45), and 4) irreversible changes on air or oven drying samples (Wesley). Another common volcanic soil is pumiceous sand. They are light-weight, have rough surface and are easily crushed compared to "conventional" soils.

Atterberg limits are used to determine how a material behaves with different water content and to understand the deformability and the firmness of the soil. There are four states for the soil: solid – semi-solid – plastic – liquid. The Atterberg limits determine at what water content those changes of state occur. The liquid limit is defined by the water content (percentage) of the sample as it transitions from the plastic state to the liquid state. The plastic limit represents the water content when the soil begins to crumble when rolled into a 3 mm diameter thread. The plasticity index is represented by the difference between the liquid and the plastic limit. A large liquid limit indicates high compressibility and high shrink swell tendencies while a large plasticity index indicates low shear strength (Lewis and McConchie (1997), NZ4402:1986 standard test method).

5.3.4.1. Composition

Samples that were suspected to contain a high clay content were analysed under the XRD to determine their composition. Only the 9 phi fraction was analysed for clay identification. The 9 phi fraction was obtained using the settling tube method. The settling tube method is governed by Stokes’ law which is based on an ideal settling velocity (v) that assumes a spherical diameter. Samples were collected after 8 hours of settling at a pipette insertion depth of 10 cm.

$$Stokes'law: v = Cd^2$$

where,

v = *velocity*

and

$C = [(ds\text{-}df)\ g] / 18\mu$

where, ds = *density of the solid*

(*density of quartz* = 2.65 g/cm^2)

df = *density of fluid (water)*

g = *gravitational acceleration* (980 cm/s^2)

μ = *viscosity of the fluid*

d = *diameter*

(source: Lewis and McConchie, 1997)

Results from the XRD analysis are presented in Table 31. The composition of the fines showed the presence of clay minerals such as Kaolinite, Illite and Illite-Montmorillonite. They were present in the Rotomahana mud, the 1886 Tawarera basalt as well as in the Maungataketake base surge and fall samples. The presence of calcite and halite in the Mauntaketake samples can be explained by the sampling location (the samples were taken from an outcrop by the beach and the interaction of the outcrop with sea water would explain the presence of such minerals).

TABLE 31: X-RAY DIFFRACTION RESULTS

	QUARTZ	ALBITE	KAOLINITE	ILLITE-MONTMORILLONITE	ILLITE	CALCITE	HALITE	TOTAL
Sample Label	BLUE	GREEN	YELLOW	BLACK	PURPLE	RED	PINK	
TAUPO UNIT 3	present	present						0
TAUPO UNIT 4	10	90						100
TAUPO UNIT 3 DISTAL		present?						0
ROTOMAHANA MUD	50	30	5	15				100
1886 BASALT	40	45	15					100
BASALTIC BASE SURGE	45		5		15	35		100
BASALTIC FALL MIX	15				5		80	100
ANDESITE		100						100

*Values are estimates and given as percentage composition of the crystalline material present in the air dried sample.
*Colours refer to the database lines on the XRD scan for each sample (see Appendix W).

5.3.4.2. Atterberg Limits (Liquid and Plastic Limits)

Atterberg limits (liquid and plastic limits) from samples with high clay content were obtained using the cone penetration test for the liquid limit and rolled threads for the plastic limit. All of the results were obtained in accordance to the NZ4402:1986 standard test method.

Two samples contained enough fines to be submitted to the Atterberg limit tests; the Rotomahana mud and the Mauntaketake base surge samples. Results from the tests are presented in Table 32 and detailed data is presented in Appendix V.

TABLE 32: ATTERBERG TEST RESULTS

Results	Rotomahana mud	Mauntaketake base surge
Cone penetration limit (CPL)	40	30
Plastic limit (PL)	27	28
Plasticity index (PI)	13	2

*Note: material used in those tests were from the whole soil sample, the samples were slightly air dried and the results were obtained in accordance with the NZS 4402 : 1996 Test 2.3 test method.

The values from the Atterberg limit tests and water content were plotted in a plasticity chart and they plot under the Casagrande A' line in the low to intermediate plasticity zone (Figure 45). From this chart, the Maungataketake base surge is part of the ML group and the Rotomahana mud is part of the MI group. They are classified as silt with low to intermediate plasticity respectively. During the preparation process for the cone penetration test of Taupo Unit 4 (Rotongaio ash), it was determined that the samples was too sandy to be submitted to the test.

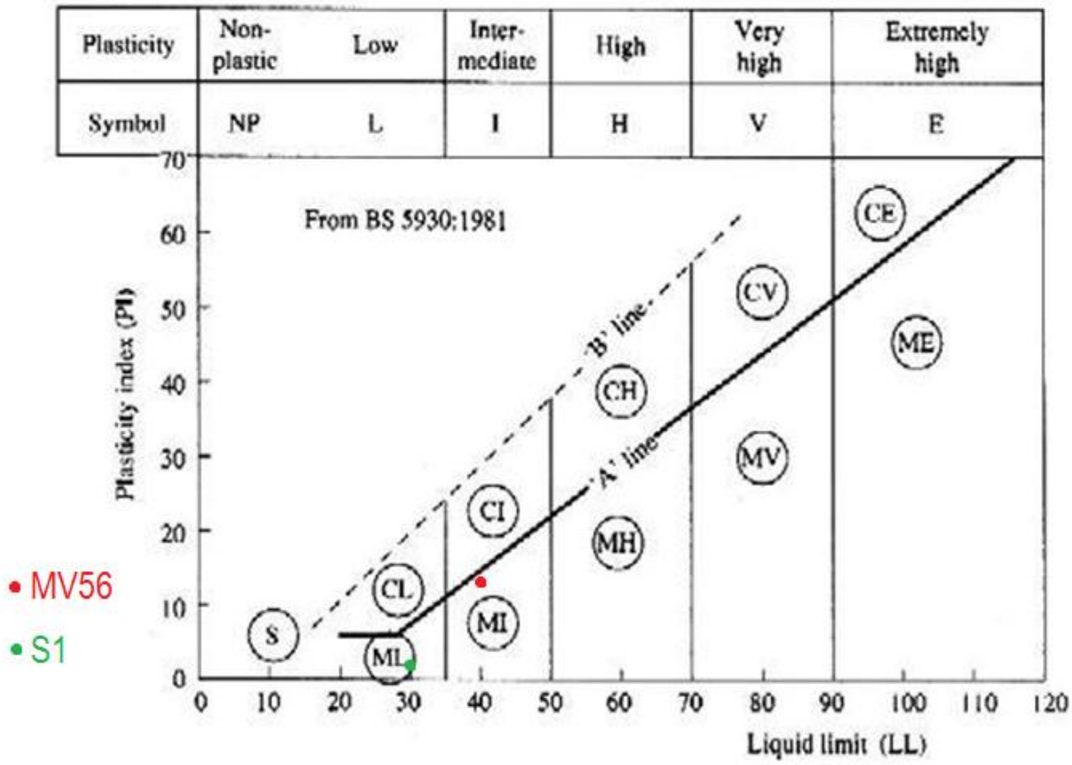


FIGURE 45: CASAGRANDE PLASTICITY CHART

5.3.5. Angle of Repose

The angle of repose is defined by Wang *et al.* (2013) as being the angle made by the heap of the deposited granular materials in the slope or the run-out of the deposits. In this study, the angle of repose is defined as the maximum slope angle at which grains are stable, above this value the material will flow (ASTM C1444-00 Standard). It is dependent on the particle size, shape and bulk density of the material (ASTM website, 2013). Angle of repose is generally used in risk hazard analysis for collapse or avalanche but it also has use in the industry for slope stability.

The angle of repose measurements were based on the ASTM C1444-00 Standard and Chik & Vallejo (2005) using a funnel test method and was reinforced with secondary test involving a free flowing scoop technique. The ASTM C1444-00 standard has been produced to measure the angle of repose of uniform free-flowing mold powders. It has been withdrawn without replacement in December 2005 due to limited used by the industry (ASTM website, 2013).

Samples used in this project were composed of multiple clasts size, ranging from ash to lapilli. The experiment was modified following the method used by Chik & Vallejo (2005) for testing the angle of repose of binary granular materials. Different funnel aperture sizes were used depending on the sample particles size. The funnel test presented multiple difficulties such as irregular particles flow and sorting. Extra measurements were taken from another technique using a scoop to poor the material in a pile. The same angle measurements were taken from the pile.

5.3.5.1. Funnel Test Set-Up

The set-up was based on the ASTM standard and is represented by a funnel standing on a ring stand at 3.81 cm height (1.5”) (Figure 46). Because of the large variation in grain size, two different set-ups were used for finer and coarser material. Funnel diameter for samples with fine particles was 11.75 mm or 18.25 mm while for coarser particles was 26.26 mm. The funnel aperture was chosen so that it was at least ¼ of the size diameter of the largest particle.

A clean sheet of paper (A3 or A4 size) over a flat and polished surface was used as a flat surface and a concrete block was used as a rough surface. The sheet of paper was replaced in between each sample. The rough surface was initially cleaned with water and later cleaned using an air compression devise in between each sample test.

It was important that the material was flowing in one uniform flow and for this to happen, a stopper is necessary. Because of the large size of the particle normal stopper could not be used, so a piece of wood was used to stop the particles from falling while the funnel was filled up and was then removed to release the sample as a uniform flow.

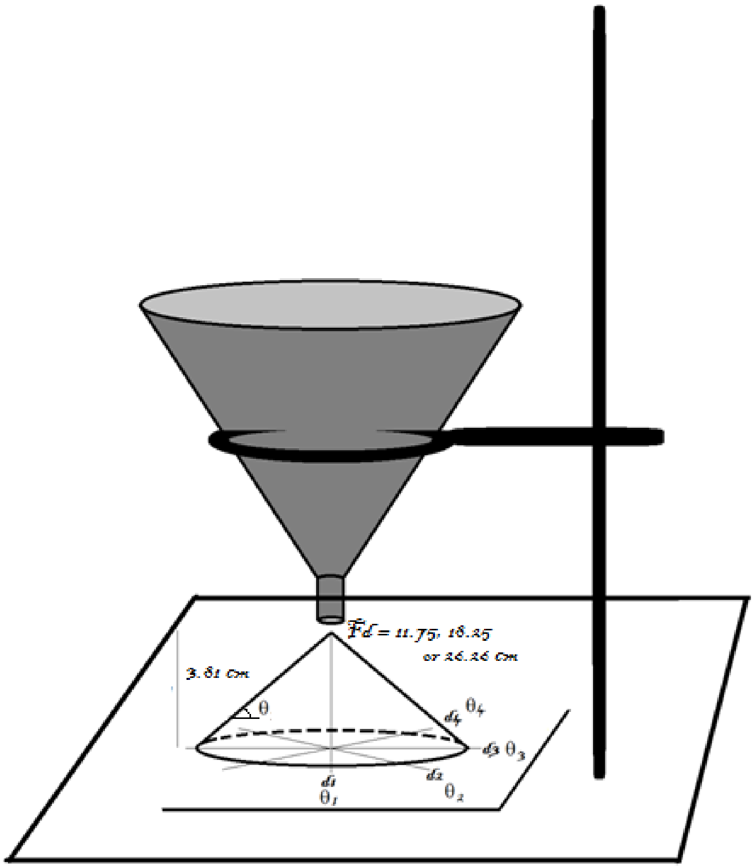


FIGURE 46: SCHEMATIC REPRESENTATION OF THE FUNNEL TEST SET-UP

Procedure and calculation

Measurements were made on non-treated and air dried bulk samples using 2 different methods to limit the uncertainties related to the imprecision of the data collection (Chik and Vallejo, 2005). The first method is through direct measurement of the observed angle of repose called the “direct angle”. The average of four different direct measurement (<1, <2, <3 and <4 in Figure 46) is calculated using a protractor to represent the angle of repose. The second method uses the “base length” measurement, which represent the diameter at the base of the cone and the cone “height”. The angle of repose is then calculated from this value and using the formula:

$$\theta = tan^{-1}\left[\frac{2H}{D_a}\right]$$

where, θ *= angle of repose*

H = cone height (1.5 inch or 3.81cm)

D_a *= average base length*

The angle of repose was tested for dry samples on flat and porous base (Figure 47). Each sample would be tested 5 times and the following measurements would be taken for each test:

- *d = Base length (4 times)*
- *H = Vertical height*
- θ *= Direct angles (4 times)*

FIGURE 47: REPRESENTATION OF THE SMOOTH AND ROUGH SURFACE USED IN THE EXPERIMENT. SCALE: THE LENGHT OF EACH PHOTO IS ABOUT 6CM

Base length is measured using a 150 mm long caliper with a precision of 0.01 mm. The vertical height was measured in 2 different ways. The first was measured from the base of the funnel to the base of the platform and should be the same for all measurement; 3.81 cm (1.5 inch) or and the second was from top of the pile to the base of the platform.

The data ranges from 34-39 degrees for a flat surface (36.5 ± 2.5), and from 31-40 degrees on a rough surface (35.5 ± 4.5). The highest results were from Taupo Unit 4 (Rotongaio ash) sample while the lowest were from the andesitic samples. The Rotongaio ash sample presented high cohesion between particles and was able to stay stable at high angles.

The overall results show no significant difference between the results from a flat or a rough surface with angle of repose around 36 degrees. And all the values are close to scree angle of repose range.

TABLE 33: ANGLE OF REPOSE MEASUREMENT RESULTS

	Flat Surface			Rough surface		
	Average			Average		
	Min	Max	Average	Min	Max	Average
TAUPO UNIT 2 PROXIMAL	34	41	37			
TAUPO UNIT 4 PROXIMAL	39	49	44	39	48	43
TAUPO UNIT 3 DISTAL	34	40	37			
TAUPO UNIT 3 DISTAL	35	42	39	34	40	38
TAUPO UNIT 5 DISTAL	34	39	37			
KAHAROA FINE	35	42	38	36	42	40
KAHAROA COARSE	33	42	38	36	43	39
ROTOMAHANA MUD	36	41	38	36	41	38
1886 BASALT	33	37	36	31	37	34
1886 PROXIMAL	34	40	37	32	40	36
POUTU FINE	31	41	35			
POUTU MEDIUM	34	38	36	33	39	36
ANDESITE	36	40	38	30	32	31
ANDESITE	31	37	35	30	34	32

The angles of repose obtained in this study were varied (Figure 47). Reasons for this range of values can be there are multiple factors that influence the angle of repose. Previous study showed that the size particles, surface area, surface texture, shape (angularity and roughness), gradation, sorting, compaction and surface moisture of the particles may affect interaction forces such as frictional force and cohesive force, affecting the angle of repose (Burkalow (1945), Yang *et al.* (2009), Froehlich (2011), Wang *et al.* (2013), Samadani & Kudrolli (2008), Chik & Vallejo (2005), Pohlman *et al.* (2006)). It was not always possible to get a gentle and continuous flow from the funnel. The tests were conducted on air dried samples, which could leave a small amount of humidity, thus increasing the likelihood of cohesiveness. This has been observed for certain samples. When using the scoop to create the material piles, the flow was more controlled but a preferential orientation was formed on the cone with the width of the scoop. The presence of large clasts on the pile was observed to create a steeper slope as it was stopping the fines from going down the pile. It was also observed that the angle of repose of the pile resulting from the scoop method represented a natural angle while the standard angle represented a maximum angle of repose at which the slope is stable but not at rest. For the purpose of this study the collapse processes were not studied.

Conflicting results on angle of repose variation with grain size distribution are present in the literature (summarized in Table 34). Chick and Vallejo (2005) studied the angle of repose of binary granular material mixture for various percentages of fines on two different bases (smooth and rough). The results showed that on a smooth (glass) surface, the angle of repose decreases with an increase in percentage of coarse material and contrarily the angle of repose increases on a porous (rough) surface. They explain this result due to the increasing the frictional resistance by increasing contact area when fines are present in the system. Yang et al. (2009) studied the angle of repose of nonuniform sediment using rotating drums. Their research focussed on investigating the angle of repose for a variation of weight ratio from two uniform sediments. They observed that the angle of repose increases slightly with the size particles mean diameter in a binary sample. This was explained by the smaller grains filling up the voids between larger grains and producing a stable slope. Another study from Froehlich (2011) studying the effects of median particle diameter on the mass angle of repose (the angle at which a mass of sliding particles comes to rest) of open-graded riprap also showed that it increases with an increases in particle size. A recent research from Wang et al. (2013) studying the angle of repose from Sichuan earthquake (2008) induced landslide debris deposits showed that the angle of repose measured in laboratory decreases with any of the particle sizes increase. The grain sizes from the presented researches respectively ranges from 0.1 mm-1.16mm, 1.5-11 mm, 0.9-40 mm and 3.2-355 mm. In this research, the volcanic material from the North Island of New Zealand grain sizes ranges from 0.008-16 mm.

The sorting of the particles affect the angle of repose. With increase in grain size, the angle of repose decreases when sorted and increases when non-sorted (Burkalow (1945), Miller & Byrne (1966)). Sorting has been observed while taking measurements of the volcanic materials. Sorting was created when the fine grained particles would pass through the funnel first, leaving the larger particles to fall at the end. The method used in Wang et al. (2013) could have been better to measure the angle of repose and avoid sorting, creating more repeatable data. Froehlich (2011) angle of repose were produced using truck with front-end loader. This technique would be similar to actual clean-up techniques and may be more relevant to the study. Thus sorting during measurement is more realistic for the purpose of this study. With sorting, the fines would have a stronger control on the angle of repose.

Wang et al. (2013) mention that the compaction may have an effect on the angle of repose as their results showed that the angle of repose increase with the increase of compaction, but compaction was not taken in consideration in this study as the material well mixed before measurements.

Burkalow (1945) showed that the angle of repose inversely varies with fragment density and height of fall of material on a free cone and directly varies with angularity, roughness, degree of compaction and increase of moisture (only until saturation where it varies inversely afterwards). Samadani and Kudrolli (2008) showed that the angle of repose of a wet sample is greater than a dry sample because of the cohesive forces being created by the liquid.

The experiment for the angle of repose was based on the method used by Chik & Vallejo (2005). Their experiment showed that the angle of repose changes with different grain size percentage on different base (smooth and rough). Their research showed that for a low percentage of fines the angle of repose on a smooth surface decrease while it increases on a rough surface. . The angle of repose on rough and smooth surfaces from volcanic tephra measurement does not show comparable results with the Chick & Vallejo (2005) (Figure 48, Figure 49). Results from the smooth surface can be represented by a linear curves and have a small variation between the angles. The results on a rough surface are more variable for fine samples. This can be because the samples are not only binary but are composed of multiple different clast sizes. It can also be due to the larger size of the clasts compared to the roughness of the surface.

TABLE 34: ANGLE OF REPOSE STUDY SUMMARY

Test description	Results	Grain size range	Reference
Angle of repose of binary granular material mixture for various percentages of fines on two different bases (smooth and rough).	Smooth base: Angle of repose decrease with increase in size particles mean diameter Rough base: Angle of repose increases with increase in size particles mean diameter	0.1- 1.16 mm	Chik and Vallejo (2005)
Investigate the angle of repose of nonuniform sediment for a variation of weight ratio from two uniform sediments using rotating drums.	Angle of repose increases slightly with increase in size particles mean diameter	1.5-11 mm	Yang et al (2009)
Effects of median particle diameter on the mass angle of repose of open-graded riprap.	Angle of mass increase with increase with size particles mean diameter Angle of repose increase with angularity, mixture nonuniformity and particle size.	0.9-40 mm	Froehlich (2011)
Angle of repose from Sichuan earthquake (2008) induced landslide debris deposits	Laboratory angle of repose decreases with any of the particle sizes increase.	3.2- 355 mm	Wang et al. (2013)

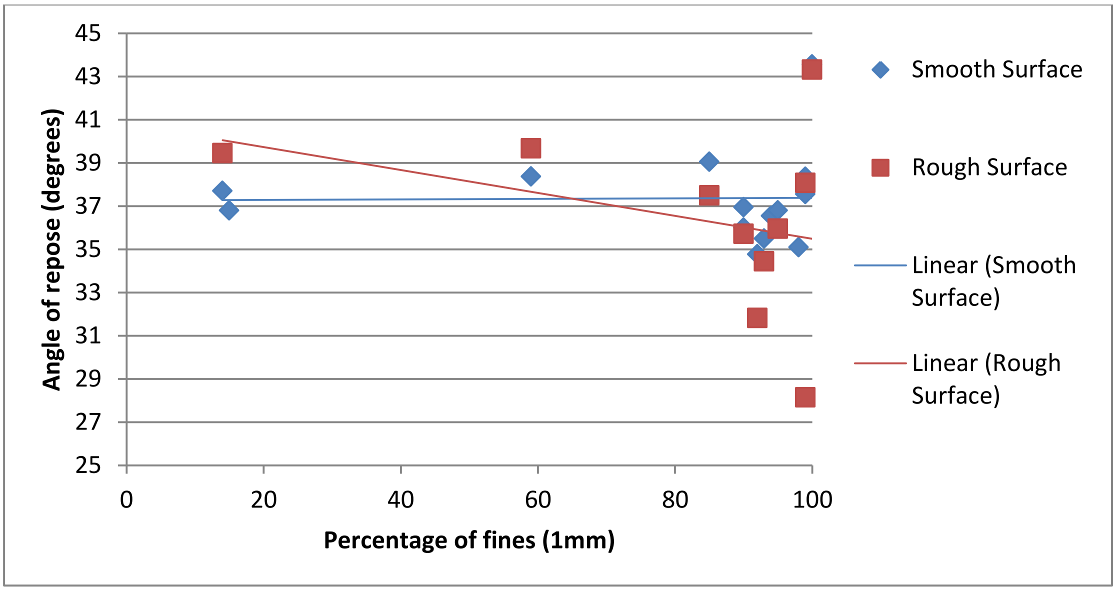


FIGURE 48: ANGLE OF REPOSE WITH PERCENTAGE OF FINES VARIATION WHERE FINES ARE <1 MM

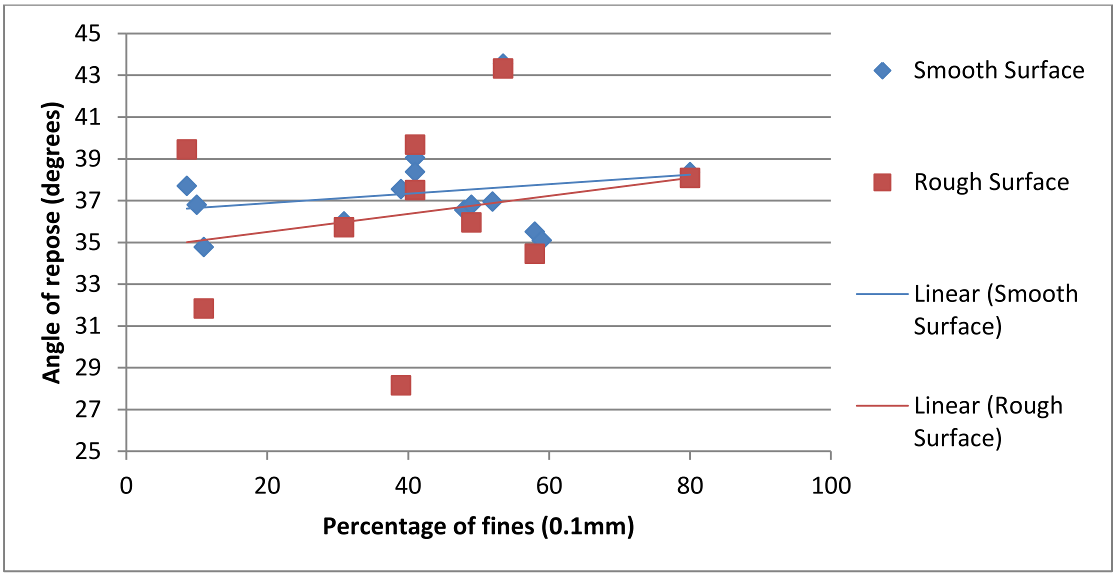


FIGURE 49: ANGLE OF REPOSE WITH PERCENTAGE OF FINES VARIATION WHERE FINES ARE <0.1 MM

5.4. Implication for "Tephra Clean-Up"

This section discusses the implications of the findings for tephra clean-up of the sample tested. A wider implication for general fine grained sediment is presented in chapter six (discussion).

Density, particle size, clay content, moisture content, method of loading are important in clean-up operations such as removal, transport and disposal. It is important in transport because truck load depend on those properties; a truck can carry a larger volume of low density material in one load, but the cargo body volume is constrained by the particle size.

Common trucks that could be used for the transport of fine grained sediment following a disaster, based on trucks used during the Christchurch clean-up, are 4x2, 6, 8 or 10 wheel, truck and trailer and articulated trucks (Table 13). The loading and volume capacity of the truck will differ depending on the trailer attached to the truck, but there is a direct relation between the amount of wheels and capacity (number of wheels $\propto$ volume and loading capacity). A list of common cargo volume was constructed based on truck profile sheets (Table 35) (Truck & Trailer (China) Ltd website, 2013). This information was used to determine the amount of sediment that could be carried depending on the density of the tephra samples (Table 36).

Table 36 shows that for a dense material such as the Mauntaketake deposits, only 2m^3 of material can be carried by a 5 ton capacity truck. If the cargo volume of a 5 ton truck is around 7-8 m^3, only a quarter of its maximum loading capacity will be used. Trucks will maximise their volume capacity for materials with densities close to 1000 kg/m^3, but not necessarily to their maximum loading capacity. Multiple trips would be required when loading or volume capacities are exceeded. A proper selection of trucks would be based ideally on the properties of the material to be cleared to optimise the clean-up. However, it must be anticipated that during a disaster response, the available trucks might be limited and they will not be used to their full capacity. Thus, a prior registration list of resources present and available in the area should be assessed. It should include front end loaders, trucks and equipment to load the trucks. Material density should be used for calculation when planning for disaster clean-up strategies and costs of an extensive clean-up. Grain size also should be considered as it contributes to the maximum volume that a truck can contain. Special care for the resource use to clear and transport volcanic material should also be planned for corrosion.

TABLE 35: COMMON TRUCKS USED FOR DISASTER CLEAN-UP AND CARGO BODY VOLUME

Truck	4x2	6 wheel	8 wheel	10 wheel
Cargo body volume (m^3)	7- 8	10-20	19-27	10-64

TABLE 36: VOLUME IN M3 OF TEPHRA MATERIAL THAT CAN BE TRANSPORTED FOR DIFFERENT TRUCK LOADING CAPACITY.

sample	Density		Volumes in m^3 Categorised by truck loading capacity in Tonnes					
	kg/m3	t/m3	5	8	10	15	20	40
BASALTIC FALL COARSE	2057	2.06	2	4	5	7	10	19
BASALTIC FALL MIX	1820	1.82	3	4	5	8	11	22
BASALTIC BASE SURGE	1811	1.81	3	4	6	8	11	22
ANDESITE	1654	1.65	3	5	6	9	12	24
TAUPO UNIT 4 PROXIMAL	1582	1.58	3	5	6	9	13	25
KAHAROA FINE	1409	1.41	4	6	7	11	14	28
1886 DISTAL BASALT	1333	1.33	4	6	8	11	15	30
ANDESITE	1329	1.33	4	6	8	11	15	30
ROTOMAHANA MUD	1279	1.28	4	6	8	12	16	31
TAUPO UNIT 3 PROXIMAL	1267	1.27	4	6	8	12	16	32
TAUPO UNIT 5 DISTAL	1258	1.26	4	6	8	12	16	32
POUTU FINE	1257	1.26	4	6	8	12	16	32
TAUPO UNIT 3 DISTAL	1242	1.24	4	6	8	12	16	32
ANDESITE	1239	1.24	4	6	8	12	16	32
POUTU MED	1236	1.24	4	6	8	12	16	32
ANDESITE	1208	1.21	4	7	8	12	17	33
KAHAROA COARSE	1128	1.13	4	7	9	13	18	35
1886 PROX.	1082	1.08	5	7	9	14	18	37
1886 BASALT	1059	1.06	5	8	9	14	19	38
POUTU COARSE	1047	1.05	5	8	10	14	19	38
TAUPO UNIT 6 PROXIMAL	990	0.99	5	8	10	15	20	40
TAUPO UNIT 3 DISTAL	941	0.94	5	8	11	16	21	42
TAUPO UNIT 5 PROXIMAL	887	0.89	6	9	11	17	23	45
TAUPO UNIT 2 PROXIMAL	749	0.75	7	11	13	20	27	53
TAUPO UNIT 2 DISTAL	740	0.74	7	11	14	20	27	54
1886 PROX.	628	0.63	8	13	16	24	32	64

The angle of repose can be used to determine if the slope angle of the disposal site is convenient for storage. The grain size, density and composition can be used to determine the potential impact of the surrounding area and to determine the proper strategy to control them (remobilisation by wind or by water, leachate). Those results complement the review from Johnston *et al.* 2001.

The angle of reposes from this study are similar to the common stable slope angles (Table 37) and it can be concluded that slope stability techniques can be applied if needed during storage.

Density and composition are also important when considering future land use of the disposal site as high density and high clay contents in soils decreases the presence of pore space in between the clasts. This limits the water and air penetration in the ground, preventing plant growth (CSS, 2013).

TABLE 37: COMMON STABLE SLOPE RATIO AND RELATED ANGLE FOR VARYING SOIL CONDITION

Soil conditions	Common stable slope ratios	Slope angle degrees
Most in-place soils	¾:1 to 1:1	45-53
Loose coarse granular soils	1 ½:1	34-45
Heavy clay soils	2:1 to 3:1	18.4-26.5
Soft clay rich zones or wet seepage areas	2:1 to 3:1	18.4-26.5

5.5. Future Use of Tephra Materials

Volcanic materials have been used in various industries for centuries. It is used in abrasive, ceramic glaze material, as an additive to cement, sweeping compound, black top highway dressing and more (Carey et al., 1952). But the use of fresh material in recovery work presents a more complex goal as the geotechnical properties of young volcanic product are different from aged products and they have not been fully investigated (Orense et al., 2006).

Generally, some reconstruction needs to be considered following a disaster. For example, building, roads or embankment may have to be rebuilt. Recycling the debris or sediments deposited by the disaster into the rebuild is practical (resourceful) and presents multiple advantages. It returns the land to a reusable form restores land use by clearing them, it can increase the local incomes of the affected area and decrease the material costs of recovery.

An example where recent eruption volcanic debris were reused comes from Mount Pinatubo eruption in the Philippines (1991). Large quantity of volcanic tephra deposited (5-8 billion m^3) and re-deposited materials through secondary lahars during rain fall were used in road, building and flood control construction (Kirk *et al.*, 2000, Shield, 1998, Orensen *et al*,. 2006). Material is characterised as a well-graded coarse sand to silt sized material (gravelly sand, more than 85% passing 2.36 mm sieve). Well graded materials are likely to be more compactable because of their wide range of particle sizes that can easily be arranged to produce a denser bulk (Road research Laboratory, 1961). Shield (1998) investigated the use of lahar deposit material in the construction of flood control dykes following the eruption as the quality of the dyke structure was revised following its failure in 1997. Shields (1998) studied the geotechnical properties of the lahar deposits and of the dyke structures and concluded that the failure was due to loose design specification during construction. The use of well graded sandy lahar was found to provide an adequate embankment material (Shields, 1998, Kirk *et al.*, 2000). Shields (1998) recommended the use of the material if compaction regulations are respected and design allows for piping and liquefaction. Kirk *et al.*, 2000 recommend the material if vesicularity of the sample is factored into the asphalt mix and if permeability of the mix is meeting the standards developed by the strategic highway research program (SHRP).

Orense et al. (2006) also studied the Pinatubo deposit as well as deposits from Mt Unzen and Izu-Oshima (1990-1986, Japan). They investigate the fresh volcanic materials permeability, compaction, strength, deformation behaviour in drained conditions and liquefaction characteristics. Their conclusions were that geotechnical characteristics of the deposit varied with sampling sites (upstream from the volcano = high compressibility and low cyclic strength; downstream from the volcano = dilative tendencies and high liquefaction strength) and that future uses of those volcanic materials would vary. The volcanic sand from Izu-Oshima had fairly high shear strength and good compaction geotechnical properties, similar to the standard Japanese sand used in construction materials (Toyoura sand) and could be used in future construction material for engineered structures. Mt Unzen samples had low strength and were very compressible and could be used as embankment or foundation if improved with cement. The Pinatubo samples would require additional mixing before being used as construction materials.

A list of potential use of volcanic tephra materials for road or construction material with related material properties are:

- Asphalt mix: well graded coarse sand to silt and non-plastic material
- Construction material: high shear strength and good compaction
- Embankment or foundation (if improved with cement): low shear strength and compressible, well graded sands (Peters, 1982 from Shields, 1998)
- Component of mixes made with a “gap-graded” aggregate structure such as hot rolled asphalt (HRA) mix and as a component of an asphalt concrete (AC) mix.
- The presence of plastic fines (less than 0.425 mm sieve) can prevent proper adhesion between the aggregates and bitumen in a hot mix and lower the quality of the film surrounding the particles. Thus plastic fines in a hot mixes should be avoided and non-plastic material should be considered.
- Geotechnical properties may vary from different site

The knowledge that volcanic material weathers into clay minerals (plastic fines) needs to be considered against the expected lifetime of the construction when using fresh volcanic material into building materials.

Density and moisture content are important properties during construction, with 90% of maximum dry density compaction being the lowest level acceptable (Rolling & Rollings 1992)

5.6. Summary

Physical properties of fine grained sediment (<1 mm) deposited by a disaster affect its clean-up through clearing, transport, storage and future usage.

- Transport: density, grain size, compaction, moisture content
- Stability of the stock pile: angle of repose (density, grain size, compaction), moisture content
- Future use of the land: quantity and composition of fine particles, compactibility

The density and grain size affects the transport of material and the loading on roofs from tephra. The grain size affects the compaction and the angle of repose affects the stability of the stock pile. The quantity and composition of fine particles affects the future use of the land where it will be stockpile and the clean-up. It also helps to determine if the site is large enough to contain the sediment. The composition determines whether the material is toxic and if it needs special handling care. Properties can also be used to determine if the material can be used in construction material. It is thus important to understand the material to optimise the clean-up and the recovery of the affected region.

The grain size, density and composition can be used to determine the potential impact of the surrounding area and to determine the proper strategy to control them. Common slope stability techniques can be applied to volcanic tephra samples if needed during storage.

In conclusion, using fresh volcanic material in road, building or flood control construction requires good understanding of the material properties and precaution during design and construction to extra care, but if well planned, it can be economically beneficial.

The geotechnical result from this study shows that volcanic tephra could be used in road or construction material but the properties would have to be further investigated for a New Zealand context.

Chapter 6. Discussion and Conclusions

6.1. Project Summary

6.1.1. Objectives and Investigation Methodology

The primary objective of this thesis was to assess resources, time and cost required for fine grained sediment (<1 mm) clean-up in urban environment following a disaster with the goal of supporting city disaster response planning and decision making. It aims to minimise the consequences of disasters by identifying the challenges of cleaning-up an urban environment following a disaster based on lessons learned following the Christchurch urban liquefaction ejecta clean-up (2010-2011 earthquakes sequence). It would provide support in planning for resources, costs and time required to provide a rapid and effective recovery.

This was done through identification of geotechnical properties from potential fine grained sediments (<1 mm) deposited by disaster such as volcanic tephra from the North Island of New Zealand and reviews of the Christchurch liquefaction ejecta clean-up following the 2010-2011 earthquake sequences. A series of semi-structured interviews supported by relevant literature and media report were used to make a preliminary qualification of the Christchurch liquefaction ejecta clean-up (costs breakdown, time, volume, resources, coordination, planning and priorities). The results showed that further analysis of the costs and resources involved was required. The analysis of Christchurch City Council road management database (RAMM) was used to calculate a more accurate cost and resources inventory of the Christchurch ejecta clean-up. This data was supported by a statistically based spatial and temporal analysis using the program *ArcGIS.* Laboratory analysis of young volcanic tephra from the New Zealand's North Island was performed to identify their geotechnical properties (density, granulometry, plasticity, composition and angle of repose).

6.1.2. Qualitative Study of Christchurch Liquefaction Ejecta Clean-up

This section looked at the experience of cleaning-up liquefaction in Christchurch city during the Canterbury earthquake sequence in New Zealand's central South Island. It investigated the logistics, resources and financial costs needed to conduct a large-scale fine grained sediment (<1 mm) clean-up operation in an urban area.

The induced widespread liquefaction phenomena across the Christchurch urban area on four occasions (4 Sept 2010; 22 Feb; 13 June; 23 Dec 2011), that resulted in widespread ejection of silt and fine sand. This impacted transport networks as well as infiltrated and contaminated the damaged storm water system, making rapid clean-up an immediate post-earthquake priority. In some places the ejecta was contaminated by raw sewage and was readily remobilised in dry windy conditions, creating a long-term health risk to the population. Thousands of residential properties were inundated with liquefaction ejecta, however residents typically lacked the capacity (time or resources) to clean-up without external assistance.

The liquefaction ejecta clean-up response was co-ordinated by the Christchurch City Council and executed by a network of contractors and volunteer groups, including the '*Farmy-Army*' and the '*Student-Army*'. A series of semi-structured interview were conducted with key members from some agencies involved in the clean-up. Results showed that the duration of clean-up time of residential properties and the road network was approximately 2 months for each of the 3 main liquefaction inducing earthquakes; despite each event producing different volumes of ejecta. Preliminary cost estimates indicate total clean-up costs will be over $NZ 25 million. Over 500,000 tonnes of ejecta has been stockpiled at Burwood landfill since the beginning of the Canterbury earthquakes sequence. This is in the context of approximately 4 million tonnes of demolition waste from both the Central Business District (2 million tonnes) and residential-suburban-commercial (2 million tonnes) zones in addition to 4 million tonnes of demolition waste from repair of roads plus water and sewer pipes.

6.1.3. Quantitative Study of Christchurch Liquefaction Ejecta Clean-up

The goal of this chapter is to quantify the resources, time and cost required for general fine grained sediment (<1 mm) clean-up in urban environments following a disaster based on the Christchurch liquefaction ejecta clean-up. The result shows:

- Analysis of data collected within this thesis suggests a total estimated cost of approximately NZ$40 million for the Christchurch City liquefaction ejecta clean-up following the 2010-2011 Canterbury earthquake sequence.
- The duration of clean-up time of residential properties and the road network was approximately 2-3 months for each of the three main liquefaction ejecta event; despite each event producing different volumes of ejecta.
- 9-10% of the road city network was impacted during the Darfield and Christchurch 2 earthquake and 22% for the Christchurch 1 quake
- 13 - 33% (186 km – 418 km) of the southern sections of the Christchurch City road network was impacted by liquefaction ejecta and required clearing of the material.
- The cost of clean-up per km is highly variable throughout the events, with the average values per event ranged between $NZ 5,500/km and $NZ 11,650/km.
- A maximum rate of 338 road segments per week was observed (2nd week of Christchurch 1 clean-up)
- The geospatial results (temporal and spatial distribution analysis) of the cost and resources reflected the priority decisions made by the contractor roading management team.
- A total of 31 462 tonnes was cleaned from 151 different street segments from the 1st of March to the 8th of March.
- Cost per ton for a large volume of sediment will range from $NZ 2-12/t, from $NZ 17-28/t for a moderate volume and from $NZ 58-113/t for a small volume. In average the cost will range from $NZ 20-92/t.
- Approximate values given from the Christchurch city contractors shows that the clean-up costs are proportional to the volume of sediments.
- Interviews and quantitative analysis of RAMM data showed experience and knowledge gained from the Darfield earthquake (September 2010) clean-up increased

the efficiency of the following Christchurch earthquake clean-up events (February and June 2011).

- Road clean-up repetition needs to be considered when planning for future clean-up.

6.1.4. Fine Grained Sediment Deposited by Disasters

Some natural hazards can generate large volume of debris including fine grained sediments that can affect the efficiency of the response effort. Furthermore, clean-up operations such as collection, transport and disposal depends on the geotechnical properties of the material (density, particle size, particle shape, clay content and moisture content). It is thus important to determine the properties of the material to be cleaned. Laboratory analysis of young volcanic tephra from New Zealand's North Island was performed to identify their geotechnical properties (density, granulometry, plasticity, composition and angle of repose) to see how they differ and how they can be managed during a large depositional event that would require an extensive urban clean-up. Physical properties of fine grained sediment (<1 mm) deposited by a disaster affect its clean-up through clearing, transport, storage and future usage. Future use of the material was also addressed and concluded that the properties of the material be completely assessed before being use in construction material as geotechnical properties of the material vary from one source sediment to another and within the same disaster event. The geotechnical properties would have to be further investigated for a New Zealand context.

6.1.5. Discussion

Disasters affecting modern urban environments are increasingly better recorded and documented in all aspects (beyond the destruction and/or devastation) due to technological advancements and protocol implementation. This project exemplifies how many aspects of disaster clean-up can be preserved by varying means: from interviews, daily wireless reporting by clean-up contractors, to 3D intensive time sequence GIS maps and geophysical properties analysis.

Due to the interdependent nature of contributing components required to develop an efficient and cost effective clean-up strategy, many of the techniques explored, methods used and interviews of knowledge holders needs to be utilised together (in conjunction) to form the best strategy (an efficient / economical). Ideally clean-up management would consider both a general fine clean-up strategy and as many disaster specific clean-up strategy's as they have foreseeable waste generating hazards in the near future.

From the analysis of the RAMM data, critical information needed to perform a detailed spatial and temporal cost-resource analysis is presented in Table 38. Ideally, this information would be collected by trained clean-up teams that use a common recording technique.

The severity of the damage from fine grained sediment (<1 mm) are varied as observed during the Christchurch liquefaction earthquake sequence. The location of the earthquake epicentre relative to the liquefiable sediment, the magnitude of the earthquake and the local geology will influence the volume that will be produced. It is possible to categorise the three liquefaction events with different hazard intensities; Darfield is considered as a low hazard event, Christchurch 2 as a moderate and Christchurch 1 as a high hazard event. It was possible to observe similarities between the three events even though they differ in volume of sediment and hazard intensity. The similarities include the delay of a few days (two to three days) for the cleaning to begin and a strong response during the first two weeks. High initial input was such that 40% of all the cost and resources were used within the first 10 days for the events. Following this the activities slowed down with 75% of cost and resources used within the first 15 to 25 days for Christchurch 1 and Christchurch 2, and about 40 days for Darfield. All activities then plateau to low activities after three months (around 90-95%).

Impacts from different fine sediment will be varied as they do not have the same source. Liquefaction may only impact small area of the city while tephra fall may impact the entire city downwind of the eruption. Liquefaction originates from the ground and can impacts underground infrastructures and building foundations, contrastingly, tephra fall is aerially deposited and roof tephra loading needs to be addressed. Material origin and properties are important to acknowledge during clean-up and when planning to accommodate for them. For example, tephra particles are typically hard, abrasive, mildly corrosive and have the potential to damage resources used for the clean-up (USGSa, 2010).

As the communications between the public and the contractors were evolving, a more organised schedule was put in place to avoid repetition. The Darfield event turned out to be a practice for the much larger volume and distribution of sediments ejected in Christchurch 1 earthquake. Without the Darfield earthquake clean-up, the following clean-ups are expected to have been more chaotic, resulting in longer clean-up periods, more road repetition clean-up and a higher cost associated with them.

The Christchurch 2 event had the more expensive hourly cost as well as the more expensive cost per kilometer. From the experience gained from previous clean-up and the smaller volume, it was expected that the clean-up would be cheaper and faster. Multiple reasons can support this result. First, it could be attributed to the volunteer fatigue and the need of more contractors to do the job. In Christchurch 2 the student army was slowed down because the university continued to function during the final examination period. This higher cost could reflect the need of using more labour to compensate for the volunteers, or the longer time it would take to the citizen to clean-up their property before needing a final clean-up. Second, the contractors recording experience leads to a better process for delivering the data. Third, the lower peaks in Christchurch 2 are representative of the clean-up crews being more deliberate and taking their time. They were slowed as new priorities arise from the large cost of Christchurch 1. Plus, during the first event, the goal was to clean it all, but in Christchurch 2, only occupied sections were asked to be cleaned by the authorities (Hautler, pers comm., 2012). So, the experience and the slowdown of the clean-up allowed for more effective tracking of the jobs, extra resources were required to be used (suction sweeper to avoid the water system and drainage to be contaminated) and new resources were charged (water from hydrant), thus a higher hourly cost. The suction sweeper was one of the most expensive pieces of machinery for the contractor, but it assumed that cost reductions were made by protecting the drainage system.

Geospatial analysis showed that the costs and the repetition of the clean-up are mostly clustering around the highly impacted areas identified by the EQC/T&T land damage maps. There is a general trend for the total repetition of each events showing that about 40-45% of the roads were cleaned 1 time or 2-5 times and less than 2% were cleaned more than 20 times. Also, the repetition values showed that there was slightly more repetition in Darfield then during the other events. The general thought on the reasons for multiple cleaning are for Darfield the lack of preparedness, for Christchurch 1 the larger scale of the event and for Christchurch 2 the volunteer fatigue as well as an improved reporting habit but they should be included in clean-up plans.

TABLE 38: EXAMPLE OF BEST RECORDING PRACTICES SPREAD SHEET TO QUANTIFY FUTURE FINE GRAINED SEDIMENTS (<1 MM) CLEAN-UP, TO BE COMPLETED BY CONTRACTORS

Location	Date	Fault description	Quantity	Cartage Distance	Material	Cost	Notes
examples:							
GPS coordinates	To calculate clean-up time	Clean-up from street	Volume	km	machinery	per job	
Street name		Clean-up from roof	Weight		staff	per hour	
Road ID A consistent value is required to be able to link information together		Stock pile Transport					

6.1.6. Conclusion

The results from this thesis provide the best record of urban disaster clean-up in New Zealand history. It describes historical records of resources, cost and time required to clean-up the same city (Christchurch) impacted by three significantly different event; in volume and in distribution. The Christchurch clean-up experience has emerged as a valuable case study to support further analysis and research on the coordination, management and costs of large volume deposition of fine grained sediment in urban areas. It provides structure and insights into how a city might respond.

A realistic way to prepare such a city is to investigate the properties or the likely properties of the fine sediment that has the potential to invade the urban environment. North Island of New Zealand contains active volcanic regions and many cities are at risk to be impacted by large tephra fall. It is then sensible to investigate the properties of any potential tephra fall. Applying these lessons to other cities and/or with other fine sediment is the next natural progression in disaster management impact reduction via preparation. The first step in the process is taken, with the acquisition and laboratory analysis of young volcanic tephra from the North Island and the identification of their geotechnical properties. Tephra may be deposited on urban environment at similar or larger volumes to those seen in Christchurch from the liquefaction ejecta, and so, research of geotechnical properties which will influence clean-up, transport, storage and potential reuse is crucial.

Clean-up was shown not only to depend on the physical aspects of 'what', 'where' and 'how much', but was affected by the needs and contributions of the communities. A good communication with the population and a planned schedule for clean-ups are important in minimizing clean-up costs and time. The volunteer assistance can affect the cost of the clean-up as seen from the Christchurch 2 earthquake clean-up where the Student Army was less present.

The result of this thesis provide a potentially important basis for planning for future liquefaction ejecta in Christchurch as it can be a useful guide for resources planning and time required for clean-up. The extension to other fine sediments clean-up elsewhere must be treated with caution and more research needs to be done for this purpose. Future research might include the application of the findings and methods for other cities that can be impacted by fine grained sediment (<1 mm). Important values such as costs, cost/km or time could be used to update any clean-up planning with up-to-date manipulation costs.

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Appendix A – Typical disaster waste and their origin

Typical disaster waste (solid and liquid waste generated from a disaster) issues and their effects. Source: UNOCHA, 2011

Typical disaster waste origin	Typical disaster waste
Common examples	concrete, steel, wood, clay and tar elements from damaged buildings and infrastructures. Asbestos sheet exposure from collapse buildings. Parts from water and sewage distribution systems
Household furnishings	parts from the power and telephone grids such as electrical poles, wire, electronic equipment, transformers
Natural debris	clay, mud, trees, branches, bushes, palm tree leaves
Raw materials from industries and workshop	Chemicals, dyes and other (e.g. landmines)
Disaster settlements and camps	food waste, packaging materials,excreta and other wastes from relief supplies
Household cleaners	paint, varnish, solvents, pesticides and fertilizers
Healthcare waste	

Appendix B – Disaster waste associated with natural hazards. Source: (UNOCHA, 2011)

Hazard	Associated disaster waste
Earthquakes	Structures collapse 'in-situ', i.e. floor slabs collapse on top of each other, trapping waste within damaged buildings and structures. This can lead to challenges in sorting out hazardous waste (e.g. asbestos) from non-hazardous (e.g. general building rubble). Handling waste often requires heavy machinery, which communities may not be able to afford or have difficulty to access. Collapsed buildings may overlap across streets, making access difficult for the search and rescue and relief operations. Quantities of waste are high compared to other disaster types since all building contents normally becomes waste.
Flooding	Floods often lead to mass displacement, which in turn requires shelters and camps and leads to large volumes of household wastes. Initial damage depends on the structural integrity of infrastructure, while building contents are normally damaged extensively. Mould may be present and timber may have begun to rot. Buildings are typically stripped by owners and waste placed on roads for collection. Waste is often mixed with hazardous materials such as household cleaning products and electronic goods. Flooding may bring mud, clay and gravel into affected areas, making access difficult once the floodwater recedes. Removal may be required for relief and recovery operations. The mud, clay and gravel may be mixed with hazardous materials, requiring further assessment before dumping.
Tsunami	Strong tsunamis can cause widespread damage to infrastructure, spreading debris over large areas. Debris is often mixed with soils, trees, bushes and other loose objects such as vehicles. This makes waste difficult to handle and segregate.
Hurricanes typhoons cyclones	Strong winds can tear the roof off buildings, after which walls may collapse. Poorly constructed houses and huts can 'fold' under roof tops. Even brick and concrete walls may collapse. Waste is spread over open land, streets, and marketplaces. This would include

	roofing materials, small items and dust carried by the wind. This may cause serious problems where asbestos is present. Ships and boats are often thrown ashore and destroyed, requiring specialized waste management. Vessels that sink in harbours need to be removed. Electrical and telephone grids as well as transformers containing oil and PCBs may be destroyed.

Appendix C – Common risks by disaster waste hazard type. Source: UNOCHA, 2011

Chemical risks

- Direct dermal (skin) contact with contaminants such as pesticides, oils and acids
- Inhalation of:
  - Hazardous chemicals or products like pesticides
  - Products of incomplete combustion including dioxins/furans, poly aromatic hydrocarbons (PAH), volatilized heavy metals from uncontrolled waste burning
  - Dust, including small particulate matter (PM10) and asbestos fibres
- Ingestion of surface/groundwater contaminated by leachate from waste. This can contain high levels of organics, ammonium, heavy metals, trace organics such as PCBs, and volatile organic compounds (VOCs)
- Nuisance from odours arising from chemicals in the waste or decomposition of some waste types

Biological risks

- Dermal (skin) contact/ingestion of faecal matter/body fluids
- Direct exposure to healthcare waste
- Disease vectors from animals that congregate on or near waste:
  - Rat excreta – hanta virus, leptospirosis, plague, scrub typhus
  - Mosquitoes – malaria, dengue fever
  - Flies – bacterial infections
- Nuisance from insects, birds and rodents which are attracted to and feed on waste

Physical risks

- Collapse of waste piles, such as large piles of rubble that have been pushed to the side of a road
- Cuts and abrasions from sharp objects in waste, for example where healthcare waste has been mixed with general household waste
- Uncontrolled fires in piles of waste
- Vehicle accidents from trucks picking up, transporting and dumping waste in urban or rural areas; and
- Nuisance from smoke plumes and/or wind or wave-blown litter

Local environmental risks

- Waste that contaminates soils, rendering it hazardous to humans and animals, and/or making it unsuitable for agriculture
- Leachate from fluids passing through waste and subsequently contaminating water
- Landfill gas from decomposing organic waste, which can pose risks to humans and animals
- Infestation of rodents and insects feeding on waste
- Windblown and wave transported litter which can impact an area

Appendix D – Tephra properties

Appendix D1: Typical minerals present in volcanic tephra by magma composition. Source USGS 2009b

Magma composition	Minerals typically present
Rhyolite	Quartz, feldspar, +/- mica, +/- orthopyroxene, +/- amphibole
Dacite	Quartz, feldspar, +/- mica, +/- orthopyroxene, +/- clinopyroxene, +/- amphibole
Andesite	Feldspar, clinopyroxene, +/-quartz, +/-orthopyroxene,+/- amphibole
Basalt	Feldspar, clinopyroxene, +/-olivine, +/-orthopyroxene,+/- amphibole

Appendix D2: Density of individual tephra particles. Source USGS, 2009b from Shipley and Sarna-Wojcicki, 1982.

Type of tephra particle	Pumice fragments	Volcanic glass shards	Crystals and minerals	Other rock fragments
Density of particle	700-1,200 kg/m^3	2,350-2450 kg/m^3	2,700-3,300 kg/m^3	2,600-3,200 kg/m^3

Appendix E – Survey forms

E1: Survey forms for Christchurch City Council and the contractors

E2: Survey forms for the volunteers agencies

E1: Survey forms for Christchurch City Council and the contractors

Survey for 4 September, 22 February and 13 June

Earthquake Liquefaction clean up.

Marlene Villemure, Max Gallagher, Daniel Bristow

1) Did you have a strategic plan for the removal of liquefaction silt? Was it modified with time? How much did the September clean up experience help with the subsequent events?

2) Did you have priority areas for the clean up? If so, where? How were these decided?

3) What were the techniques used? How did they compare to the techniques used previously in similar scenarios such as snow or flood silt clean up?

4) How did you coordinate the clean up with other contractors/volunteers?

5) Was all the silt taken to the Burwood Landfill? Was there variation within earthquake events?

6) What were the resources and cost breakdowns?

- Clean up:
    - How many machines, people, days/$, transportation $/km were used.
    - Did clean up operations vary over time and for different parts of the city, e.g. were some suburbs easier or harder?
    - How long did the clean up take? Days, employee hours?
- Dumping: charge per tonne?
- Total cost?

7) What is the long term plan/solution for the silt? Are there any potential uses for the silt?

8) How is contaminated silt being managed?

9) Did you have any problems finding the resources, trucks, diggers, people etc?

10) Were there any unexpected problems? For example: Contamination issues, major delays, communication breakdowns, extra costs etc?

12) What were your Legal / contractual obligations with respect guiding how the clean up would proceeded?

13) How did you communicate important information with the public relating to the following:

- Appropriate clean up process and dumping location on street
- Clean up times: reality vs. expectations
- What did you think of the public response?

14) What are the three key lessons you would give to another city in a similar situation?

E2: Survey forms for the volunteers agencies

Survey for 4 September, 22 February and 13 June Earthquake Liquefaction clean up.

Marlene Villemure, Max Gallagher, Daniel Bristow

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

1) Could you describe your role during the last liquefaction ejecta clean-ups?

2) How did you get organized and how did you coordinate the clean up with other contractors/volunteers?

3) Did you have priority areas for the clean up? If so, where and how were these decided?

4) Did you have a strategic plan for the removal of liquefaction silt? Was it modified with time?

5) What were the techniques used? How much did the September clean up experience help with the subsequent events?

6) What were the resources and cost breakdowns?

- Clean up:
    - How many machines, people, transportation used.
    - Did clean up operations vary over time and for different parts of the city, e.g. were some suburbs easier or harder?
    - How long did the clean up take?

7) Did you have any problems finding the resources, trucks, diggers, wheelbarrow, people etc?

8) What would be the average cost/values of the clean-up? Who paid for the resources?

9) How did you receive important information from emergency managers such as?

- Appropriate clean up process and dumping location on street
- Clean up times: reality vs. expectations
- What did you think of the student response?

10) Were there any unexpected problems?

11) What are the three key lessons you would give to another city in a similar situation?

Appendix F – Data filtering extended method

Data Filtering

The RAMM data entry has pre-selected list of items within different pre-selected categories. The list for various possible road works is called “fault”. Each fault is then separated with further detailed information such as “items number”, which is further separated in “quantity” and “Cost”. This allow for easy query for normal road maintenance work. But because the system had not been modified to account for different earthquake jobs in during the Darfield clean-up, any earthquake related jobs were entered as an “other – free format” fault category and the job description was located within the “main note” column. This meant that no further filter to identify liquefaction related work was possible with RAMM. Therefore, all “other – free format” located between the 4th of September 2010 and the 21st of February 2011 was selected. After the Christchurch 1 earthquake (February 2011) data entry had been upgrade to accommodate the new type of work related to earthquake damage, including liquefaction ejecta clean-up. Data could be further filtered to only include liquefaction work under “liquefaction street-wide” or “liquefaction Iso”. All data contained within those two faults and located between the 22nd of February and the 16th December 2011 was selected.

The data was presented in a large tables containing over 18 000 entries in total (5,457 post-Darfield and 12,628 post-Christchurch 1). Appendix G represent an example of the different division column and information present in those large tables as well as a more focus table that was used for the present research.

The procedure used was to first clean data to only represent claims related to liquefaction ejecta clean-up, usually called silt or mud by contractors. For 4 September 2010 to 22 February 2011, data was filtered using key words such as liquefaction, silt, sand, mud or clean-up. Claims that the description were related to inspecting for flooding, road or earthquake repair, road or bridge closure, management or road management, earthquake response work, demolition or fence installation were not included in the results because of the risk to overestimate the results. Although this may also exclude some liquefaction clean-up activities. Some activities were challenging to differentiate as multiple activities could be reported in the same job such as carting of material to temporary sites or to the main Burwood landfill and mix of liquefaction and other earthquake waste clean-up. Claims with no dates or no costs associated with it where deleted. During this clean-up period, a validation of the “ROAD ID” was performed as well, as this acts as the primary location and task identifier for the dataset (i.e. acts as a primary key for the database). This was done by filtering for jobs without a “ROAD ID” associated with it. It was observed that for those jobs, roads were identified in the “Main Note” column. This was mostly observed for Darfield and was assumed to be a result of the lack of suitable template and experience for data collection. The RAMM road ID associated with the roads present in the “Main Note” columns was added to the table to facilitate further filter. Sometimes multiple roads were listed for the same job and cost. In these instances, the job and its related cost was split into the amount of road equally. Thirty percent of the roads data claims and 35% of costs data had to be redefined for the post-Darfield data. For the data post-Christchurch 1, most of the claims had a road ID associated with it (24% of the roads and 9% of the costs for Christchurch 1 and 1% of the roads and the costs for Christchurch 2). When a road ID was provided, it was directly used even if more roads were defined in the main descriptions. For this reason, the data must be looked at as a general area around the roads rather than a direct reflection of the road clean-up.

Then, once a general filter had been completed, the data was filtered by date and each day was separated in roads and resources. The date used was from the “Work completed date” column which represents the day that the work was done when populated and from “Actual completed date” when not populated for the Darfield data. In Christchurch 1 there was only date from the “Work completed date” column. In the original dataset, there was a “date added” category, which represent the date the work was added to RAMM. This is important for when looking at the results later as peaks cannot be a direct reflection of data entry. But this does not exclude the possibility that sub-contractors may have accumulated several days of work in one daily report. Plus, some jobs may have taken more than one day to be completed. In a situation like this work could have only been reported when the job was finished rather then spread over multiple days.

From there, the data was filtered by resources and by ROAD ID so that hours worked and costs related to resources per day and street per day could be calculated. In this stage, it was noticed that the resources quantity could have different units. They could represent the number of hours work or a material quantity. Construction materials were calculated in tonnes, and water from hydrant (began to be charged in Christchurch 2 2011 to the contractors) was measured in litres. Because the purpose was to calculate the numbers of hours necessary to clean-up the city and its related costs, construction material and water from hydrant quantities were taken out of the total costs and hours calculations. At this stage, the “main note” entry was reviewed to collect any additional information about tonnages collected or resources used that had been added as a comment. A wide range of different resources were used during the clean-up operations, so these were grouped into categories (Table 13). Excavators, loaders and bob-cats were grouped to represent the clean-up of the road, by handling and digging. The trucks represent the transport and carting of materials. The water cart and the cleaner were grouped to represent the washing and the dampening of the streets and pathways. All machineries hours include a driver.

Data Analysis

By filtering by road ID, it was possible to identify the roads that were cleaned on different days, as well as repetition of road clean-up and spatial distribution and evolution of the clean-up. The spatial evolution was compared to the Christchurch land zoning and the land damage map from Tonkin and Tailor/EQC. The T&T/EQC land damage map was produced from observation of land parcel damage during an initial drive through the city where a visual evaluation of the property land damage was done. This data does not include road damage and was produced to assist insurance claim and not academic research.

Those resources were used to quantify the story of the clean-up while the unique Road ID’s were used to map the evolution of the clean-up in a geospatially. A snapshot of tonnages removed from the street was available for the first week of March and was used to create a small detailed analysis.

Once the data was filtered and preliminary tables and graphs were produced, a visit to Fulton & Hogan was organised with Dan Lucas to validate the results and confirm that the result were properly constructed and reflected their story. It was important that the representative of Fulton & Hogan had been an active participant in the clean-up management during the past events and it is an important part of the risk management framework to communicate and consult with agencies.

Appendix G – Example of tables presenting the RAMM data

TABLE G.1: DARFIELD ORGIGINAL FILTER FROM RAMM

	Dispatch ID	Road ID	Road ID	House No	Feature	Fault	Location / Start	Actual Completed Date	Main Notes	Item Number	Quantity	Rate	Claim Amount	Work Completed Date
Description	Unique job number for each job. The same job could take more than one day and will use the same number until completed	Unique road number associate to a road or a road section. This includes only the roads from your network.	Unique name for a road or a road section.	Address. Extra information manually added	Any extra information that can be relevant to the job. Manual entry	List of items related to an activity and represent the reason for the "maintenance".	Address or road marker	Date that the job was completed.	Job description or any other relevant information concerning the job. Manually entered	Various resources, need to be selected from a previous set list	Number of hours or quantity of material	Rate of the chosen item number	Multipli-cation of item number and rate column	Day that the work was done, if not populated, use Actual completed date.
Examples	1434	1095	HAWKE ST	0	Avondale & New Brighton areas - see notes for streets	Holes (pot-holes) Deformation unknown	0	8/09/2010	Sand removal, make safe and levelling depressions by ACL - Cartage by Kwickshift Contractors Ltd Avonside, Avondale, Orrick Cr, ...	Truck & Trailer	7.5	$	$	8/09/2010
Categories used in Darfield						Other - free format		Used when work completed date was not populated						4th Sept - 21nd Feb 2010
Categories used in Post Christchurch 1						Liquefaction street-wide Liquefaction Iso		N/A						22nd Feb 2010 - 13th March 2011

* Manual entry means that the user can enter manually a description; they are not forced to select an item from a set list.

* Set list is a list of items that was chosen to represent almost all possibility that a worker can encounter in this categories. This technique facilitates future query or filtering.

TABLE G.2:FINAL FILTER USED TO EXTRACT INFORMATION

Categories	Dispatch ID	Road ID	Road ID	Fault	Maint Notes	Item Number	Quantity	Claim Amount	Work Completed Date
Category used	Unique job number for each job.	Unique road section.	Name of the road. Used road from Fulton and Hogan Christchurch network	Other – free format Liquefaction street-wide Liquefaction Iso	Job description or any other relevant information concerning the job. Manually entered	Various resources, need to be selected from a previous set list	Number of hours or quantity of material	Multiplication of item number and rate column	Day that the work was done or completed

Appendix H – Road network statistical analysis summary

	Darfield			Christchurch 1			Christchurch 2		
	Length m	Cost $NZ	Cost per Kilometer $NZ/ (Km x Rep)	Length m	Cost $NZ	Cost per Kilometer $NZ/ (Km x Rep)	Length m	Cost $NZ	Cost per Kilometer $NZ/ (Km x Rep)
road affected wk 1									
Count:	64	64	64	168	168	168	103	103	103
Minimum:	75	102	0	41	75	9	66	430	281
Maximum:	9457	73493	50967	9457	88374	56222	5735	78974	118548
Sum:	79411	472323	513859	176847	1414215	1315500	97937	1014277	1100626
Mean:	1241	7380	8029	1053	8418	7830	951	9847	10686
STD	1570	10209	10482	1182	12069	9366	985	12200	15443
road affected wk 2									
Count:	45	45	45	338	338	338	77	77	77
Minimum:	58	142	0	38	90	47	66	380	156
Maximum:	7640	34545	93522	9457	81898	220789	4008	35290	82290
Sum:	57532	202984	364268	296738	2651709	3643604	71289	574809	797170
Mean:	1278	4511	8095	878	7845	10780	926	7465	10353
STD	1653	6231	15259	1016	10368	20162	870	6787	14861
road affected wk 3									
Count:	22	22	22	230	230	230	64	64	64
Minimum:	120	90	0	41	48	45	85	575	418
Maximum:	7640	11044	18661	6329	87076	159244	3533	36187	75437
Sum:	29417	29475	36315	205432	1898622	3020527	57843	381689	517900
Mean:	1337	1340	1651	893	8255	13133	904	5964	8092
STD	1666	2453	3776	932	10921	21997	725	5603	10851

road affected wk 4									
Count:	93	93	93	87	87	87	41	41	41
Minimum:	55	77	0	64	54	54	119	902	432
Maximum:	7640	46982	68850	4488	50047	37208	4313	30644	87415
Sum:	85998	328907	447672	88755	489847	557362	41791	311767	386213
Mean:	925	3537	4814	1020	5630	6406	1019	7604	9420
STD	1216	6142	9413	1038	7975	7329	1002	7006	14891
road affected wk 5									
Count:	54	54	54	74	74	74	19	19	19
Minimum:	66	71	0	109	300	150	157	25	24
Maximum:	6449	25396	20826	6449	33275	33286	3533	31145	20524
Sum:	52173	141315	164567	80509	369177	443200	19892	122330	88446
Mean:	966	2617	3048	1088	4989	5989	1047	6438	4655
STD	1174	4751	4360	1140	5699	6872	922	8930	5521
road affected wk 6									
Count:	49	49	49	43	43	43	5	5	5
Minimum:	66	31	0	58	459	173	97	2808	6152
Maximum:	3753	13626	34092	3753	21880	59793	838	27002	28948
Sum:	34951	121116	205164	50502	200718	268703	2757	48032	65138
Mean:	713	2472	4187	1174	4668	6249	551	9606	13028
STD	810	2474	6849	938	4477	10126	248	9014	8671
road affected wk 7									
Count:	19	19	19	30	30	30	19	19	19
Minimum:	109	15	0	117	90	208	172	380	536
Maximum:	2208	5259	17552	3753	25656	76590	4496	8378	20933
Sum:	9215	29718	92811	40579	139592	185854	21163	57842	92693
Mean:	485	1564	4885	1353	4653	6195	1114	3044	4879

STD	462	1287	4992	942	4781	13633	1294	2312	4908
road affected wk 8									
Count:	18	18	18	17	17	17	35	35	35
Minimum:	66	45	0	302	165	204	103	95	129
Maximum:	7640	6723	47014	3753	5843	12981	3533	25522	53252
Sum:	18067	55339	168902	19191	37971	53417	32200	161381	238427
Mean:	1004	3074	9383	1129	2234	3142	920	4611	6812
STD	1680	2846	13716	1093	1816	3705	861	5037	9886
road affected wk 9									
Count:	17	17	17	13	13	13	24	24	24
Minimum:	109	422	0	120	702	1025	81	770	785
Maximum:	6930	59770	68939	2260	10227	19975	3533	19319	92198
Sum:	20373	126290	80773	9789	39262	71170	18772	113781	296217
Mean:	1198	7429	4751	753	3020	5475	782	4741	12342
STD	1482	19113	16071	642	2439	5195	922	4556	19792
road affected wk 10									
Count:	5	5	5	14	14	14	4	4	4
Minimum:	368	342	0	196	753	168	549	285	519
Maximum:	6930	1069	1222	4488	9248	10806	1990	12892	14767
Sum:	10172	4618	3516	14038	44742	60567	4250	20723	19534
Mean:	2034	924	703	1003	3196	4326	1063	5181	4884
STD	2459	291	517	1036	2363	3000	550	5167	5821
road affected wk 11									
Count:	11	11	11	12	12	12	9	9	9
Minimum:	202	594	168	111	1434	1016	137	525	435
Maximum:	3533	2037	7687	1411	16451	20712	1934	5541	13654
Sum:	14688	9478	16687	8446	57780	75124	7394	23578	42109

Mean:	1335	862	1517	704	4815	6260	822	2620	4679
STD	1062	554	2112	406	4727	6677	653	1732	4345
road affected wk 12									
Count:	7	7	7	3	3	3	6	6	6
Minimum:	191	499	0	360	2420	1348	222	1187	1058
Maximum:	2161	1877	2613	719	3876	6722	3753	3970	7262
Sum:	6433	5323	7928	1577	8885	10669	6298	16583	28893
Mean:	919	760	1133	526	2962	3556	1050	2764	4816
STD	567	482	942	148	650	2296	1239	1050	2048
road affected wk 13									
Count:	9	9	9	3	3	3	4	4	4
Minimum:	218	404	0	917	380	363	113	1621	775
Maximum:	2208	38343	44741	1378	7627	1845	2373	1838	15310
Sum:	8549	103178	85345	3343	9027	3320	4164	7027	20225
Mean:	950	11464	9483	1114	3009	1107	1041	1757	5056
STD	701	14520	13370	194	3276	605	825	90	5945
road affected wk 14									
Count:	4	4	4	6	6	6	4	4	4
Minimum:	472	308	0	497	550	281	298	693	843
Maximum:	549	10196	11430	3449	15671	1625	2373	4002	2350
Sum:	2028	16269	18382	8861	21129	6250	4366	8248	7376
Mean:	507	4067	4596	1477	3522	1042	1092	2062	1844
STD	30	4097	4612	932	5452	431	773	1209	610
road affected wk 15									
Count:				1	1	1	6	6	6
Minimum:				1089	145	133	120	1440	682
Maximum:				1089	145	133	2170	3459	12600

Sum:				1089	145	133	5449	11544	22703
Mean:				1089	145	133	908	1924	3784
STD				0	0	0	645	719	4030
road affected wk 16									
Count:	4	4	4	2	2	2	2	2	2
Minimum:	805	100	0	756	1411	1866	155	2770	1011
Maximum:	3533	626	646	1191	11730	2462	3533	3573	17871
Sum:	6538	1396	1135	1947	13141	4328	3688	6343	18882
Mean:	1635	349	284	974	6571	2164	1844	3172	9441
STD	1118	228	278	218	5160	298	1689	402	8430
All									
Count:	176	176	176	507	507	507	238	238	238
Minimum:	55	15	0	38	145	44	66	380	206
Maximum:	9457	191426	93522	9457	276432	220789	5735	172832	118548
Sum:	180796	1550308	969406	418410	6988087	5906792	185576	2890085	2661969
Mean:	1027	8809	5508	825	13783	11650	780	12143	11185
STD	1443	20138	10014	975	23756	19776	826	19817	16486

Appendix I: Decrease in the clean-up activity during the weekends

Week Day	Day	Hours*
S	04/09/2012	67.00
S	05/09/2012	1333.40
M	06/09/2012	5608.83
T	07/09/2012	21173.57
W	08/09/2012	16699.66
T	09/09/2012	7303.00
F	10/09/2012	14125.00
S	11/09/2012	14046.50
S	12/09/2012	3220.60
M	13/09/2012	3481.05
T	14/09/2012	620.64
W	15/09/2012	1733.50
T	16/09/2012	2425.00
F	17/09/2012	104.50
S	18/09/2012	0.00
S	19/09/2012	0.00
M	20/09/2012	1463.54
T	21/09/2012	215.50
W	22/09/2012	57.00
T	23/09/2012	193.26
F	24/09/2012	0.00
S	25/09/2012	0.00
S	26/09/2012	180.00
M	27/09/2012	464.40
T	28/09/2012	1017.20
W	29/09/2012	577.80
T	30/09/2012	4758.61
	Total	100869.56

Appendix J – Statistical relationship Co-relation Coefficient

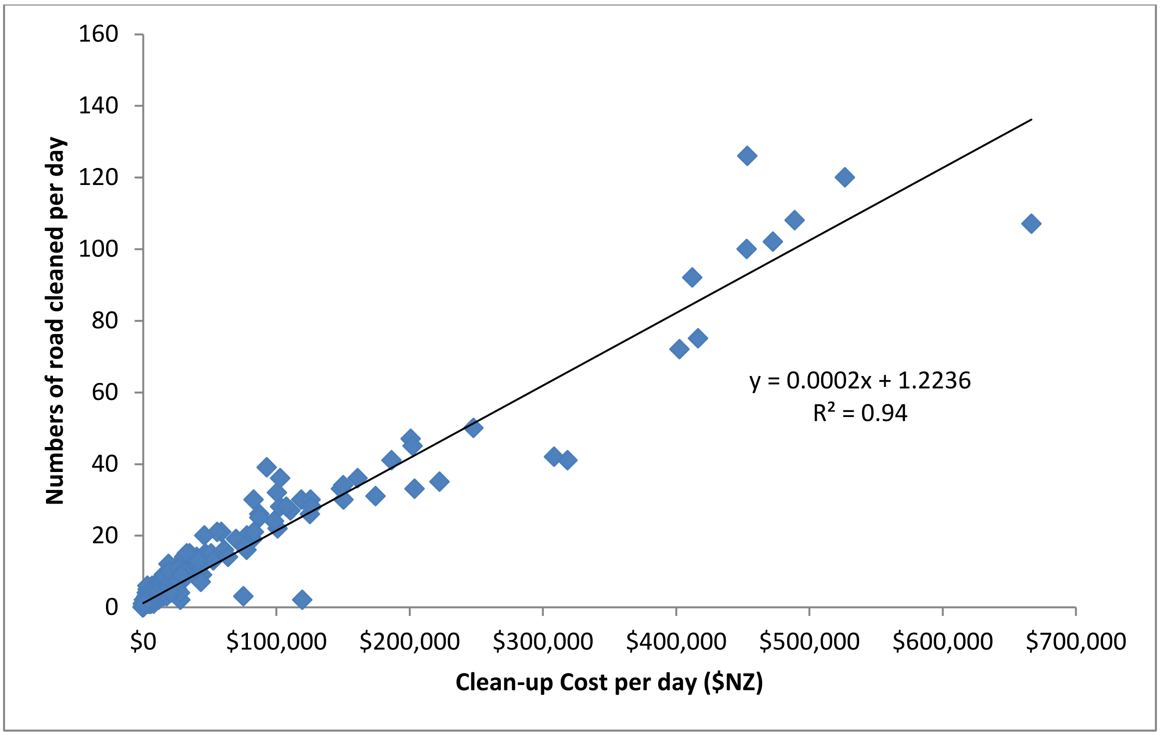


Figure J.1: Cost and numbers of road cleaned per day statistical relationship and co-correlation coefficient

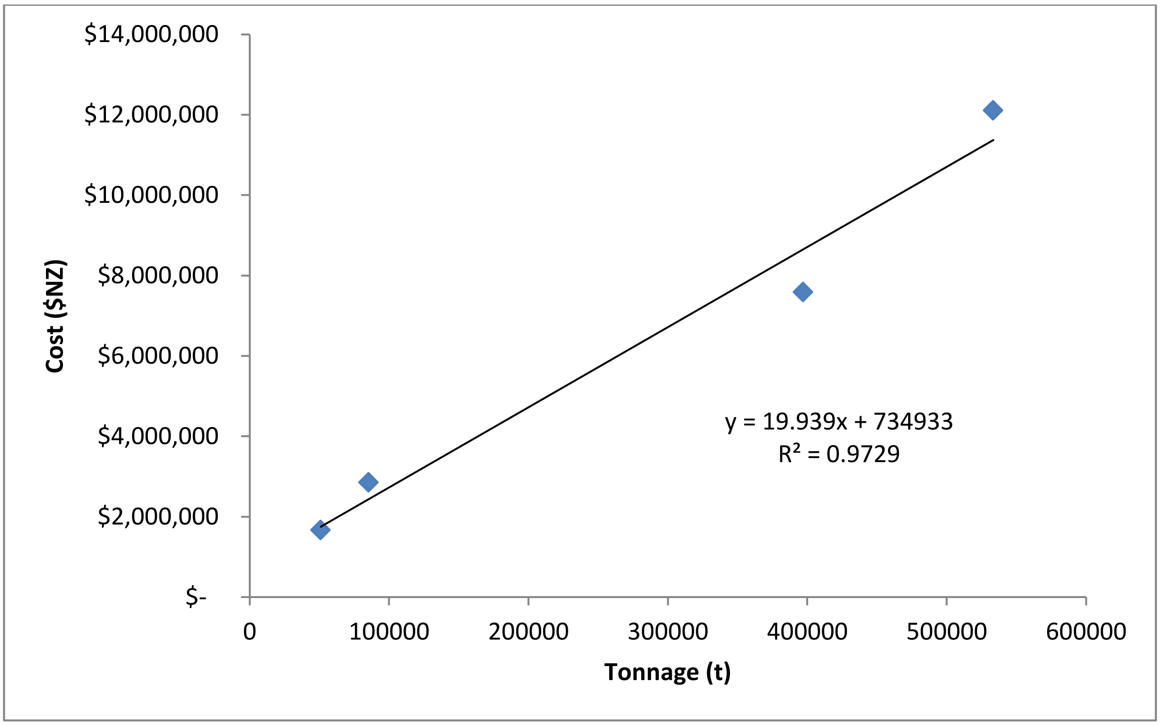


Figure J.2: Cost and volume statistical relationship and co-correlation coefficient

Appendix K – comparative curves

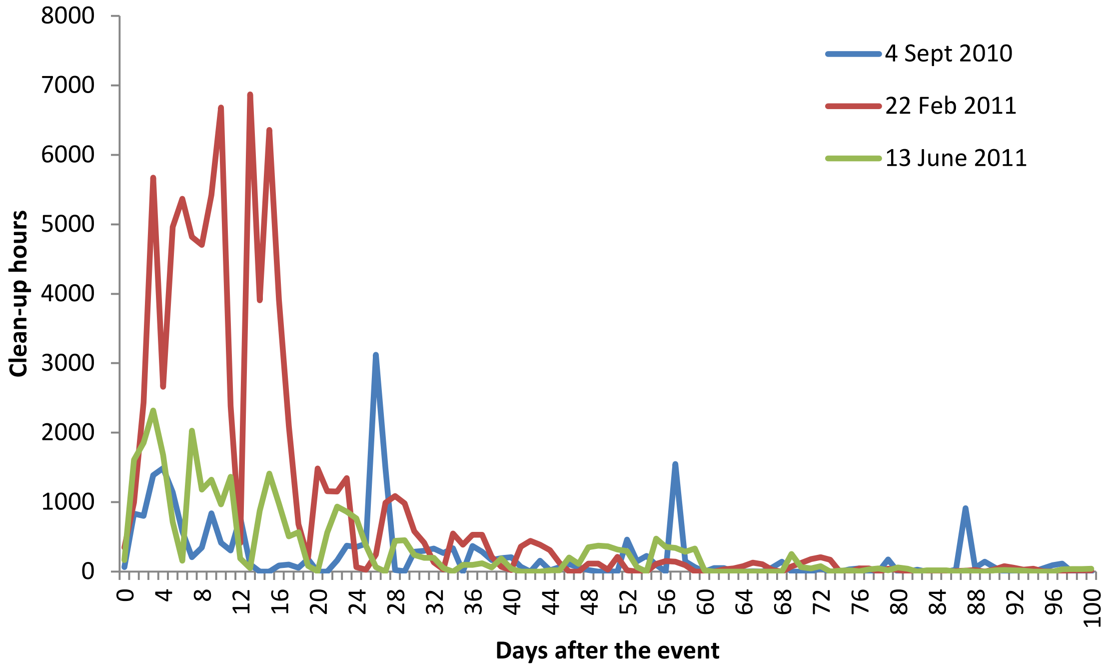


FIGURE K.1: COMPARATIVE GRAPH OF THE CLEAN-UP HOURS FOLLOWING LIQUEFACTION GENERATING EVENTS IN CHRISTCHURCH 2010-2011 EARTHQUAKES SEQUENCE

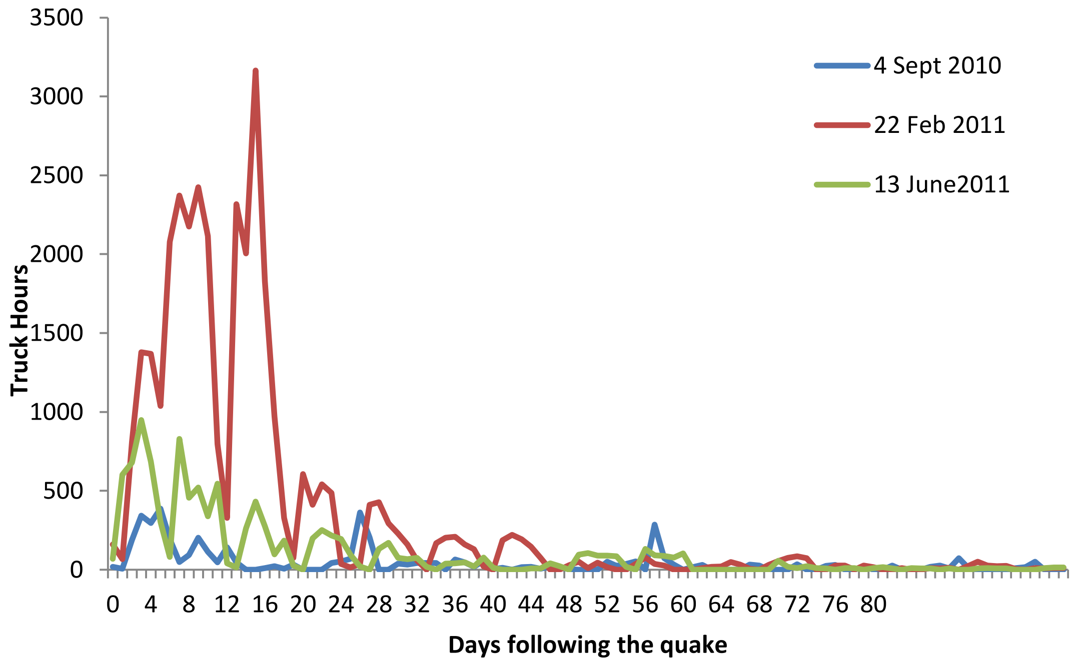


FIGURE K.2: COMPARATIVE GRAPH OF THE TRUCK HOURS FOR THE CLEAN-UP FOLLOWING LIQUEFACTION GENERATING EVENTS IN CHRISTCHURCH 2010-2011 EARTHQUAKES SEQUENCE

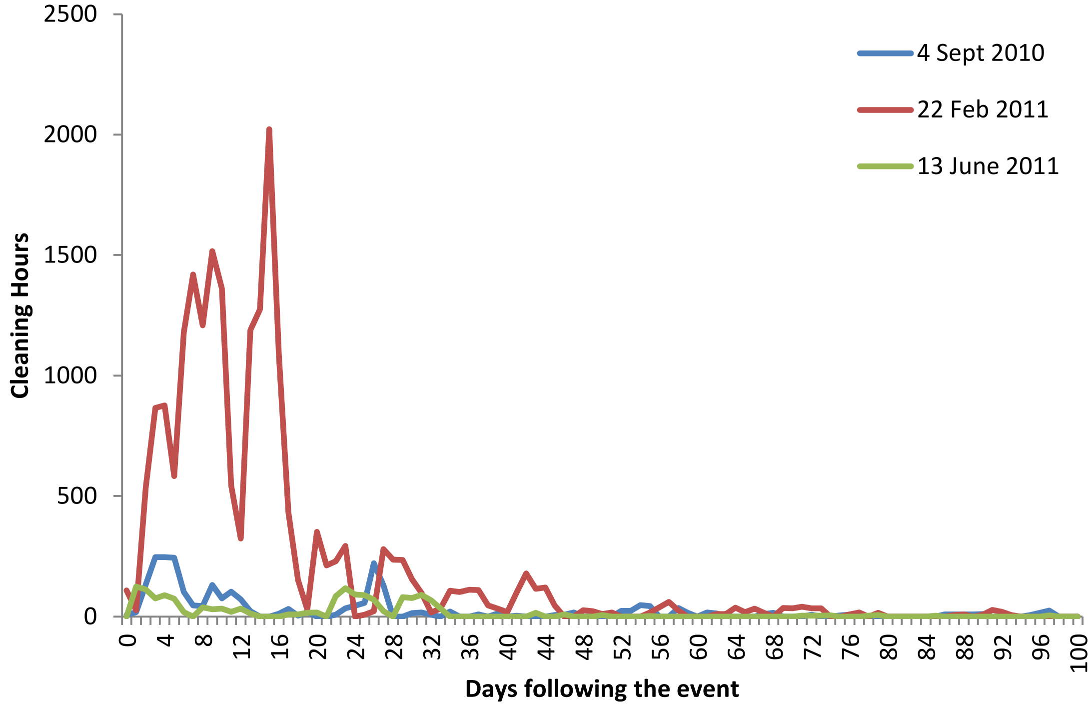


FIGURE K.3: COMPARATIVE GRAPH OF THE CLEANING EVOLUTION FOLLOWING LIQUEFACTION GENERATING EVENTS IN CHRISTCHURCH 2010-2011 EARTHQUAKES SEQUENCE

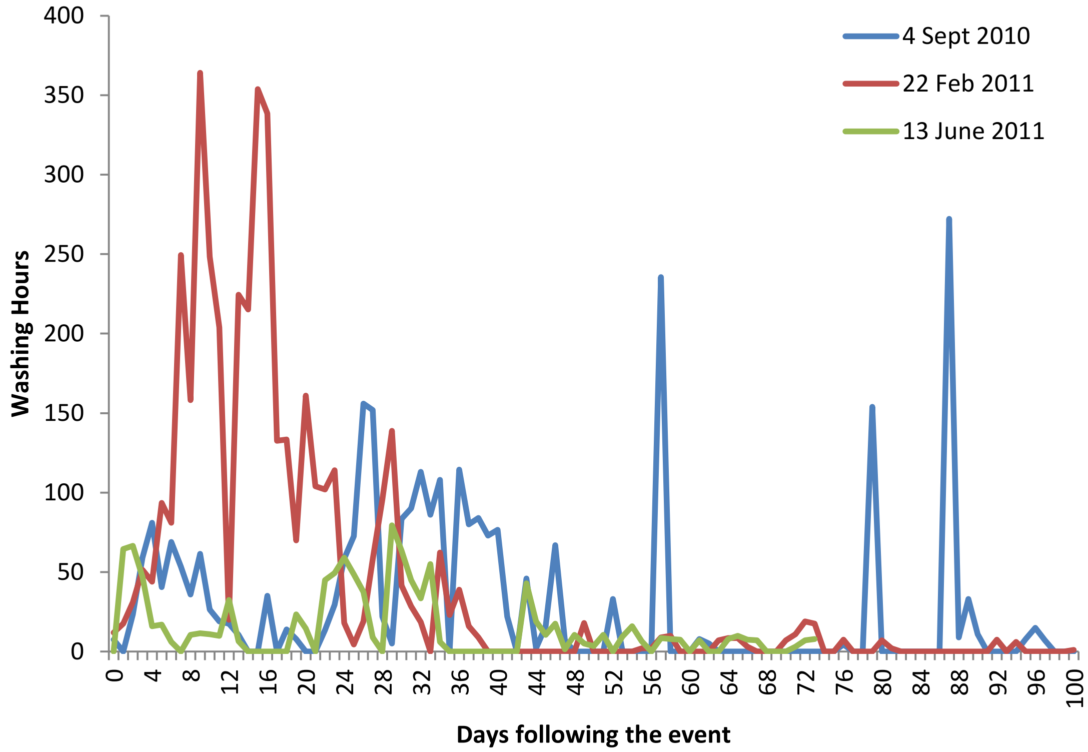


FIGURE K.4: COMPARATIVE GRAPH OF THE WASHING EVOLUTION FOLLOWING LIQUEFACTION GENERATING EVENTS IN CHRISTCHURCH 2010-2011 EARTHQUAKES SEQUENCE

Appendix L – Dates used to represent the weeks following the quakes in the spatial evolution analysis.

TABLE L.1: DATES USED TO REPRESENT THE WEEKS FOLLOWING THE QUAKES IN THE SPATIAL EVOLUTION ANALYSIS

Weeks	Dates		
	4th of September	22nd of Christchurch 1	14th of June
Wk1	4 – 10 September	22 – 28 February	14 – 20 June
Wk2	11 – 18 September	1 – 7 March	21 – 27 June
Wk3	19 – 24 September	8 – 14 March	28 June – 4 July
Wk4	25 September – 1 October	15 – 21 March	5 – 11 July
Wk5	2 – 8 October	22 – 28 March	12 – 18 July
Wk6	9 – 15 October	29 March – 4 April	19 – 25 July
Wk7	16 – 22 October	5 – 11 April	26 July – 1 August
Wk8	23 – 29 October	12 – 18 April	2 – 8 August
Wk9	30 October – 5 November	19 – 25 April	9 – 15 August
Wk10	6 – 12 November	26 April – 2 May	16 – 22 August
Wk11	13 – 19 November	3 – 9 May	23 – 29 August
Wk12	20 – 26 November	10 – 16 May	30 August – 5 September
Wk13	27 November – 3 December	17 – 23 May	6 – 12 September
Wk14	4 – 10 December	24 – 30 May	13 – 19 September
Wk15	11 – 17 December	31 Mai – 6 June	20 – 26 September
Wk16	18 December and more	7 – 13 June	27 September – 3 October

Appendix M – Weekly cost and repetition distribution maps

FIGURE M.1: WEEKLY COST DISTRIBUTION FOR THE 3 MAJOR EARTHQUAKES (WEEK 5-8)

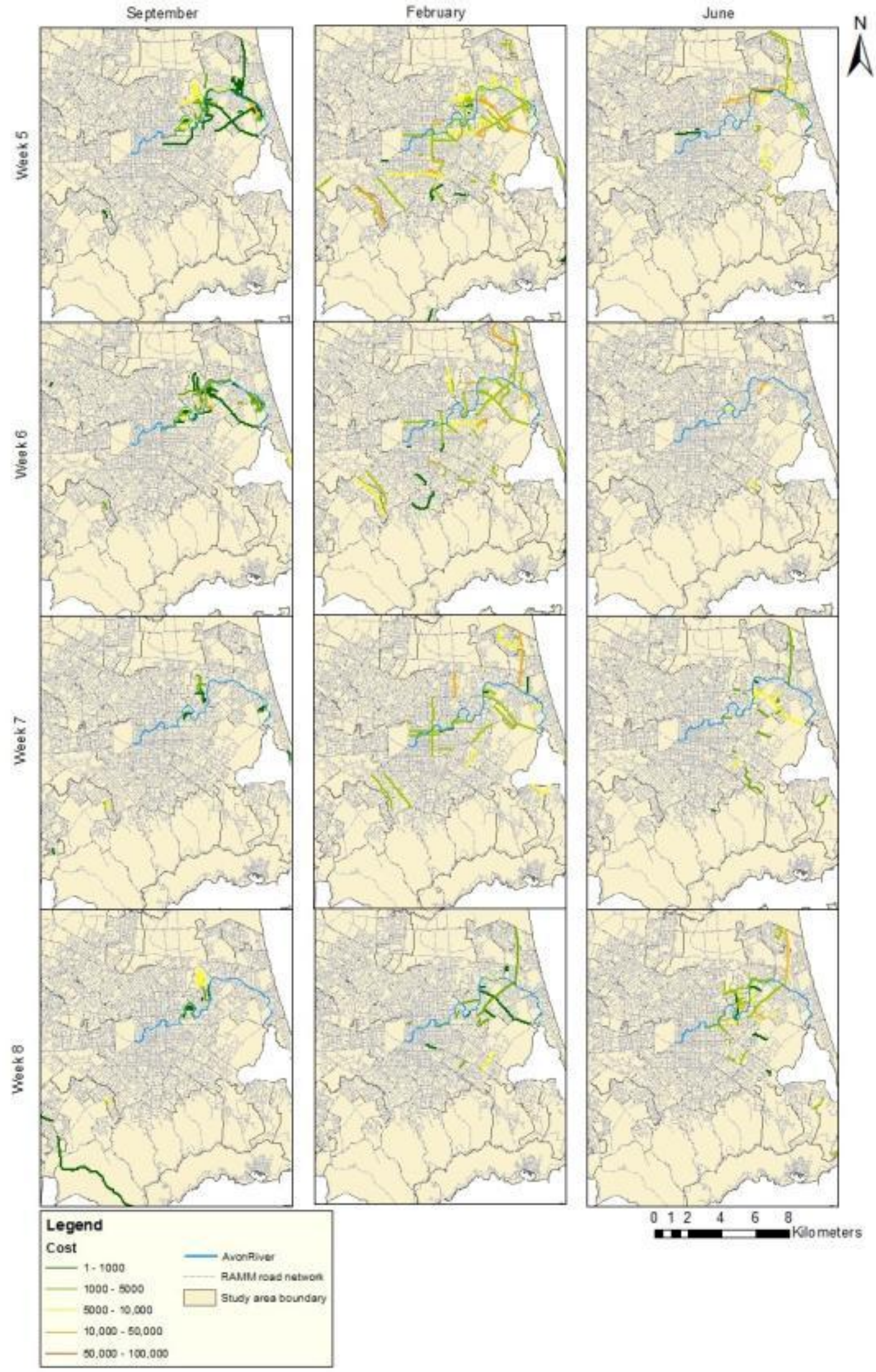


FIGURE M.2: WEEKLY COST DISTRIBUTION FOR THE 3 MAJOR EARTHQUAKES (WEEK 9-12)

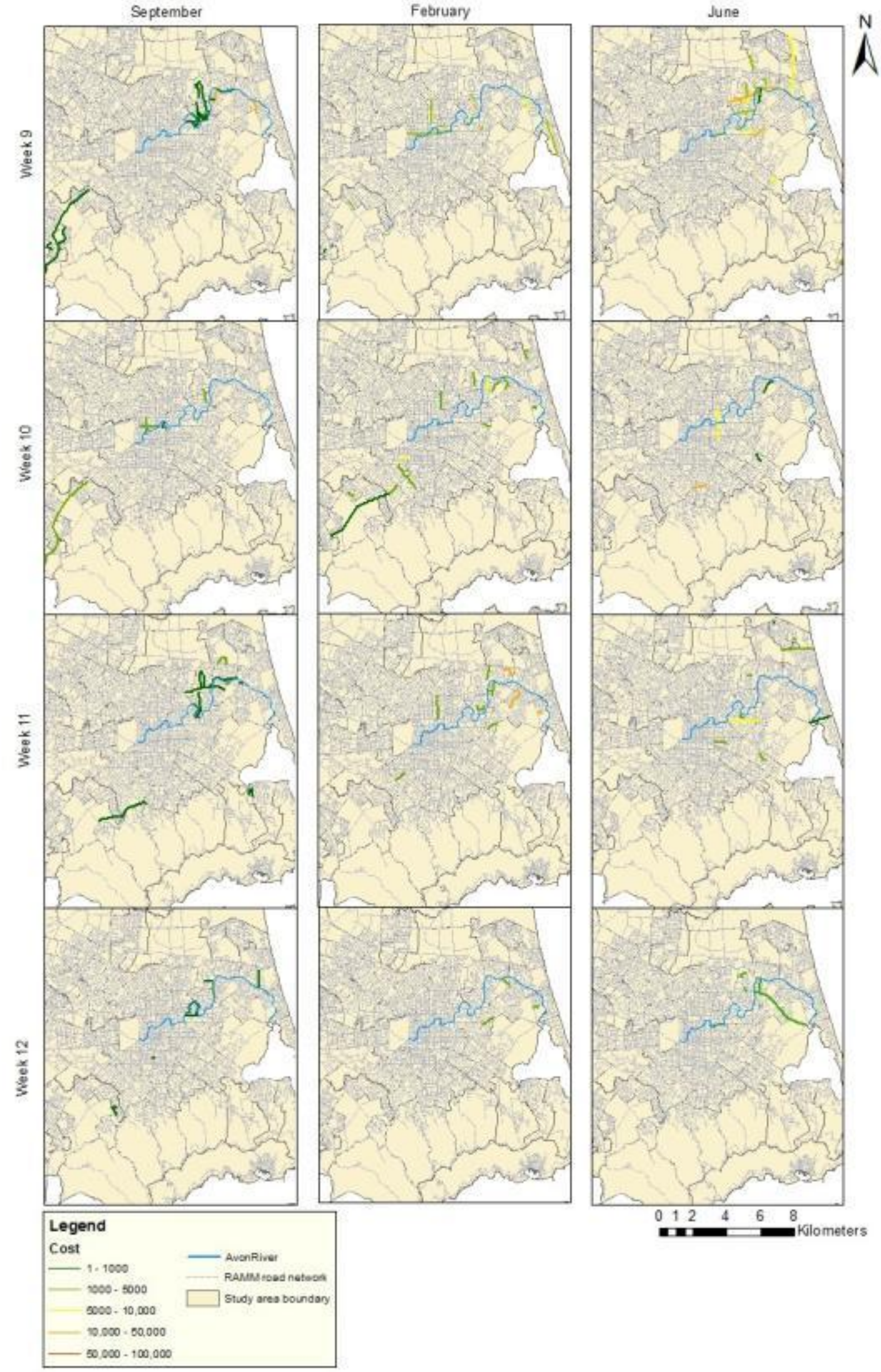


FIGURE M.3: WEEKLY COST DISTRIBUTION FOR THE 3 MAJOR EARTHQUAKES (WEEK 13-16)

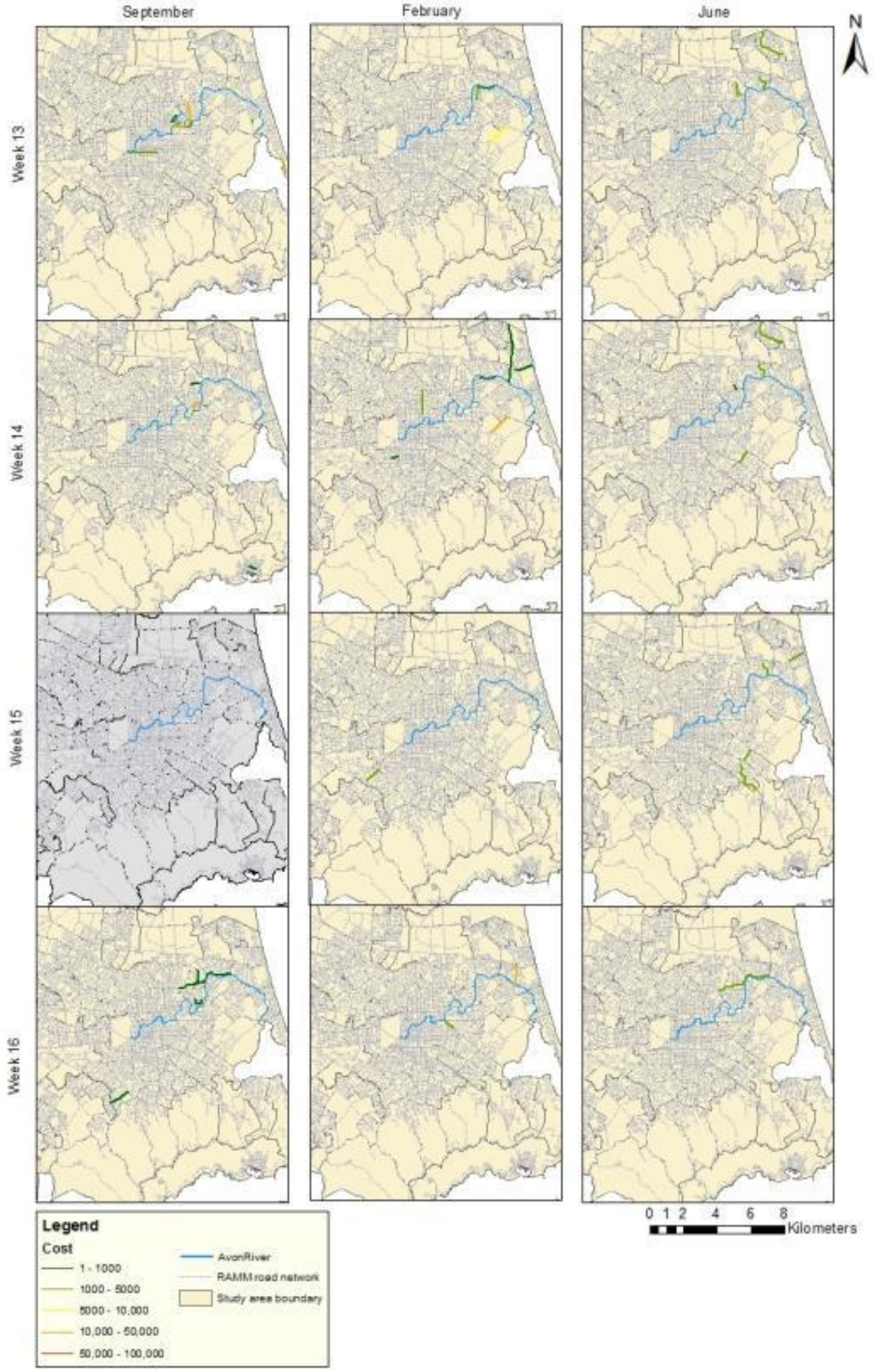


FIGURE M.4: WEEKLY REPETITION DISTRIBUTION MAPS FOR THE 3 MAJOR EARTHQUAKES (WEEK 5-8)

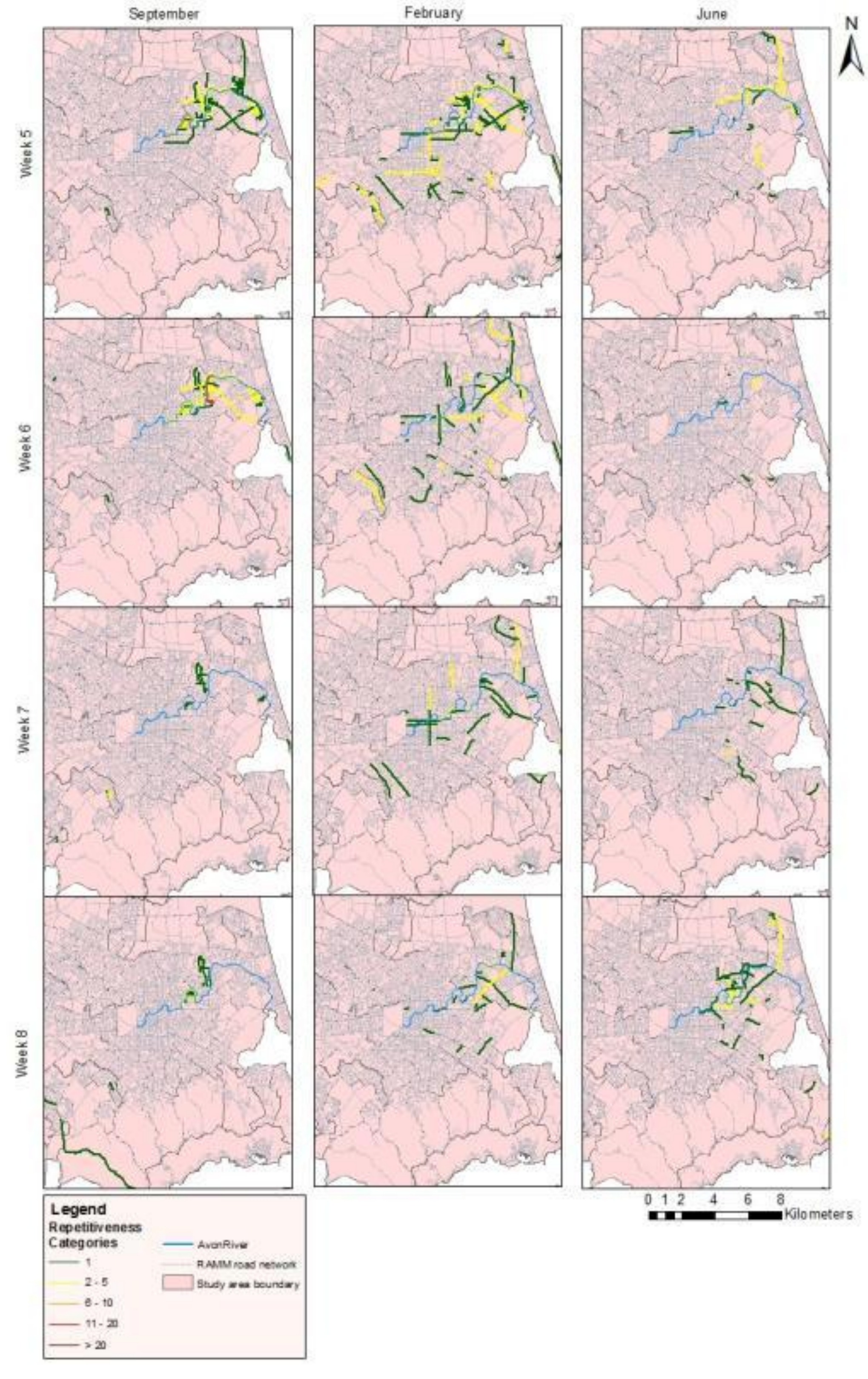


FIGURE M.5: WEEKLY REPETITION DISTRIBUTION MAPS FOR THE 3 MAJOR EARTHQUAKES (WEEK 9-12)

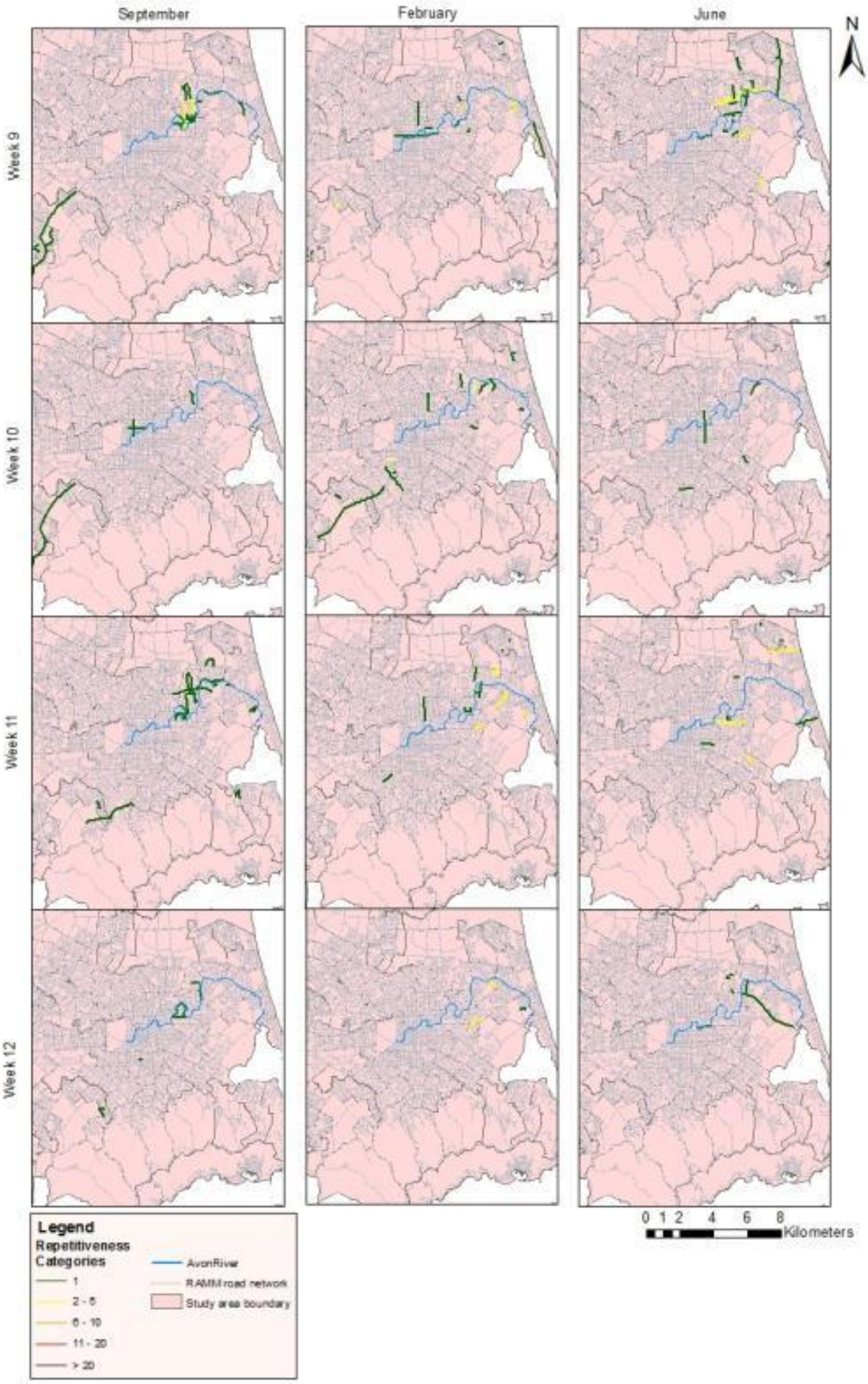
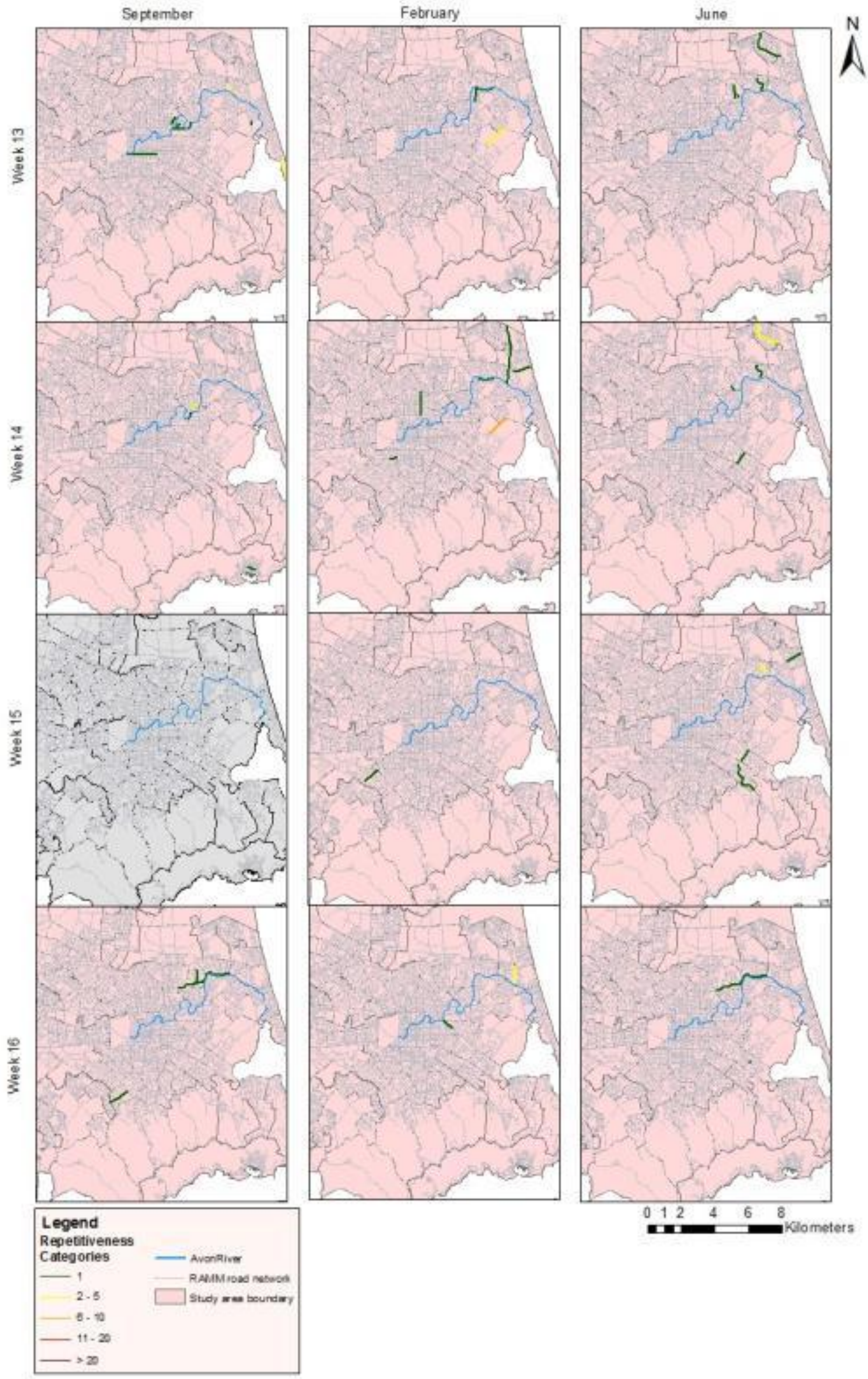


FIGURE M.6: WEEKLY REPETITION DISTRIBUTION MAPS FOR THE 3 MAJOR EARTHQUAKES (WEEK 13-16)



Appendix N: Name of the roads that have been cleaned more than 10 times during the 3 major events

Darfield	
AVONSIDE DRV 1 WEST WOODHAM RD	11
HULVERSTONE DRV 1 OFF AVONDALE RD	11
QUEENSPARK DRV	11
PAGES RD 1 NORTH	12
QUEENSBURY ST	12
CARDRONA ST	13
WAINONI RD	19
BOWER AVE	24
AVONDALE RD	26
NEW BRIGHTON RD 1 WEST ANZAC DRV	28

February	
FERRY RD 1 ST ASAPH TO FITZGERALD	11
CUTHBERTS RD	11
NEW BRIGHTON RD 1 WEST ANZAC DRV	11
MAIN RD 1	11
PAGES RD 3	11
ROCKING HORSE RD	11
ST JOHNS ST	11
WILSONS RD 1 SOUTH OF WALTHAM RD	11
QUEENSBURY ST	12
HULVERSTONE DRV 1 OFF AVONDALE RD	13
HOON HAY RD	13
WETLANDS GROVE	14
WAITAKI ST	15
QUEENSPARK DRV	15
KINGSFORD ST 1 STH NEW BRIGHTON RD	15
ST MARTINS RD 1	15
ENSORS RD 1	16
GAYHURST RD	16
HAMPSHIRE ST	16
NEW BRIGHTON RD 2 EAST ANZAC DRV	16
WAINONI RD	17
AVONSIDE DRV 1 WEST WOODHAM RD	19
BOWER AVE	19
PAGES RD 1 NORTH	24
BEXLEY RD 1	26
BREEZES RD	30

Christchurch 2	
RETREAT RD	11
GAYHURST RD	11
MORRIS ST	11
BRACKEN ST	12
LOCKSLEY AVE 1 SOUTH GLENARM TCE	13
AVONSIDE DRV 5 NORTH WAINONI RD	14
FLEETE ST	16
KINGSFORD ST 1 STH NEW BRIGHTON RD	16
QUEENSBURY ST	17
AVONSIDE DRV 1 WEST WOODHAM RD	21
KELLER ST	21
BEXLEY RD 1	25
AVONSIDE DRV 3 RETREAT TO RETREAT	28

Appendix O – Approximation hazard categories based on volume impacts for an average size properties

TABLEO.1: CHRISTCHURCH LIQUEFACTION EJECTA DENSITY AND PROPERTY MEAN AREA

Liquefaction density	1811.6 kg/m^3 (Gallagher, 2011)
	1.8116 T/m^3
Mean properties area in christchurch	1612 m^2

TABLEO.2: CHRISTCHURCH LIQUEFACTION EJECTA HAZARD CATEGORIES

Categories	Thickness	area	volume	Coverage (%)				
				5	10	25	50	100
Thickness	m	m2	m3	T	T	T	T	T
0-1mm	0.001	1612	1.612	0.1	0.3	1	1	3
1-5mm	0.005	1612	8.06	1	1	4	7	15
5-10mm	0.01	1612	16.12	1	3	7	15	29
1-5cm	0.05	1612	80.6	7	15	37	73	146
5-10cm	0.1	1612	161.2	15	29	73	146	292
10-50cm	0.5	1612	806	73	146	365	730	1460
>50cm	1	1612	1612	146	292	730	1460	2920

Appendix P – Geotechnical laboratory test method

Sampling

Sampling technique and storage used were based on Lewis & McConchie's Analytical Sedimentology reference book (yr). Five samples per unit were taken from the same horizon and the same section. Surface of the section was scraped clean of surficial weathering and vegetation prior to sampling. Samples were taken from the base of the unit in order to limit contamination from different deposit in the upper layers during sample collection. The push tube's diameter limited the sampling to units with thickness that were greater than 5 cm to avoid cross-contamination from the surrounding units. This in turn limited the sampling to proximal deposits for fine and thin units. Thin and fine distal units could not be sampled.

For the purpose of this research it was important to collect samples in their natural depositional environment. The sampling technique used was based on Engineering soil mechanics and sedimentological practices rather than the particle density approach usually taken in Volcanology research. This was necessary because pore spacing between particles is important in order to understand how tephra settle and act during cleaning. In order to collect undisturbed samples (as lowly compacted or loosened as possible) cylinders ranging from 35.50-36.53 mm internal diameter and 158-199 mm in length were inserted through a horizontal section of the deposit with the help of a large hand piston. Cylinders were previously measured, weighed and tagged in the laboratory and in-situ density was measured using the formula:

$$\delta_{in-sity} = \frac{(m_2 - m_1)}{v}$$

where; m_1 = *weight of the plastic bag or cylinder*

m_2 = *weight of the tephra sample and the plastic bag or cylinder*

v = *volume of the tephra sample within the cylinder*

Wet density was measured back in the laboratory for the Auckland samples because they were kept in the cylinders. Measurements were taken by saturating the samples in water, avoiding any flow of water going through the samples. The samples were left for 36-48 hours in a vacuum pump, standing horizontally and completely covered in water. Fine mesh was attached to both end of the cylinder with elastic bands to prevent any loss of fine particles. The wet density was measured using the following formula:

$$\delta_{wet} = \frac{(m_{wet} - M_1)}{v_{wet}}$$

where; M_1 = *weight of the cylinder (mesh + elastic bands)*

m_{wet} = *weight of the tephra sample and the cylinder*

v_{wet} = *volume of the tephra sample within the cylinder*

Dry density was measured by taking the samples out of the cylinder, transferred in a bowl and oven dried at 65 ºC degrees Celsius for 24 hours or until the weight was stable (Standard use 24 hours at 105 ºC degrees Celsius, but the possible presence of clay required a lower drying for an extended period of time). The dry density was calculated using the following formula:

$$\delta_{dry} = \frac{(m_{dry} - M)}{v}$$

where; M = *weight of the bowl*

m_{dry} = *weight of the dry tephra sample and the bowl*

v = *volume of the tephra sample within the cylinder*

Sample preparation

Samples were prepared following the method from Lewis & McConchie Analytical sedimentology and requires sample disaggregation, removal of the organic matter, cleaning and drying

In order to do proper particles size analysis, samples most be treated to disaggregate grains. This technique destroys natural agglomeration and accretion during the process. Samples were first dispersed using a gentle method consisting of adding a dispersant/defloculant to the sample and then gently manually stir it.

The samples collected were not fresh and some organic contamination was present, so it was necessary to remove the organic matter from the sample to be tested. In order to eliminate the organic, a solution of 25 % hydrogen peroxide (H_2O_2) was added to the samples. It is safe to assume that this treatment have affected the samples. Coarse organic matter that were not destroyed was later removed by hand during cleaning.

Samples were rinsed to remove all reagents using distilled water followed by a centrifuge method required because of the fine particles present. Each samples was rinsed a minimum of three times or until water was cleared.

Standard usually requires a 24 hours drying at 105 ºC degrees Celsius, but samples were dried at 50 ºC degrees Celsius oven until weight was stable to make sure no clays would be affected.

Sieving

Sieving is generally used for grain ranging from fine sand (0.06 mm) and larger. In sieving, size distribution is based on the smallest cross-sectional diameter (the smallest hole it can go through). Manual sieving was used to prevent mechanical breaking from the tephra from -4.0 to 0.0 Φ (16 to1 mm).

Laser diffraction

The sample portion that was smaller than 0.0 Φ (<1 mm) was analysed using a Saturn Digisizer II 5205. Interpretation of grading using laser sizer method provides a measure of particle area.

Appendix Q – Udden-Wentworth grain-size scale (Wentworth, 1922).

Millimeters		µm	Phi (φ)	Wentworth size class	
			-20		
	4096		-12	Boulder (-8 to -12φ)	
	1024		-10		
	256		-8		
	64		-6	Pebble (-6 to -8φ)	
	16		-4	Pebble (-2 to -6φ)	
	4		-2		Gravel
	3.36		-1.75		
	2.83		-1.50	Gravel	
	2.38		-1.25		
	2.00		-1.00		
	1.68		-0.75		
	1.41		-0.50	Very coarse sand	
	1.19		-0.25		
	1.00		-0.00		
	0.84		0.25		
	0.71		0.50	Coarse sand	
	0.59		0.75		
1/2	0.50	500	1.00		
	0.42	420	1.25		
	0.35	350	1.50	Medium sand	Sand
	0.30	300	1.75		
1/4	0.25	250	2.00		
	0.210	210	2.25		
	0.177	177	2.50	Fine sand	
	0.149	149	2.75		
1/8	0.125	125	3.00		
	0.105	105	3.25		
	0.088	88	3.50	Very fine sand	
	0.074	74	3.75		
1/16	0.0625	63	4.00		
	0.0530	53	4.25		
	0.0440	44	4.50	Coarse silt	
	0.0370	37	4.75		
1/32	0.0310	31	5	Medium silt	
1/64	0.0156	15.6	6	Fine silt	
1/128	0.0078	7.8	7	Very fine silt	
1/256	0.0039	3.9	8		Mud
	0.0020	2.0	9		
	0.00098	0.98	10		
	0.00049	0.49	11	Clay	
	0.00024	0.24	12		
	0.00012	0.12	13		
	0.00006	0.06	14		

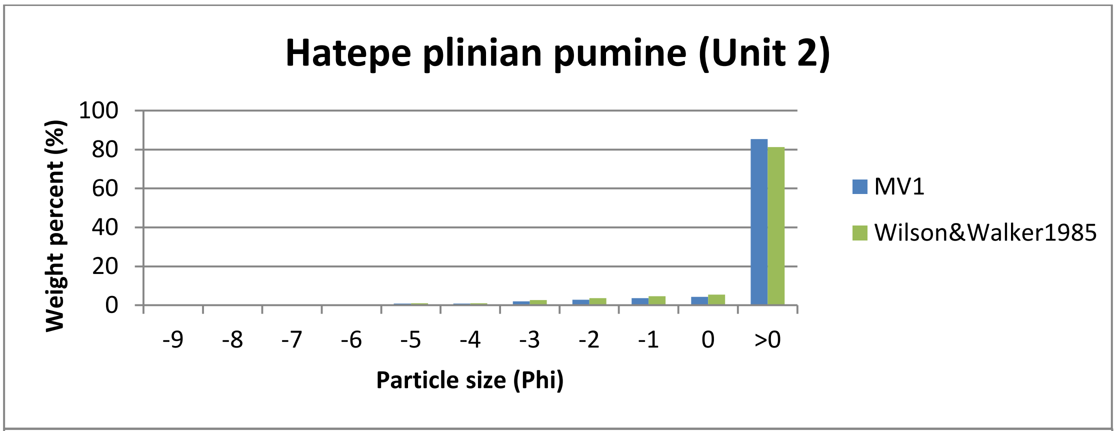
Appendix R – PUSH TUBE PROPERTIES

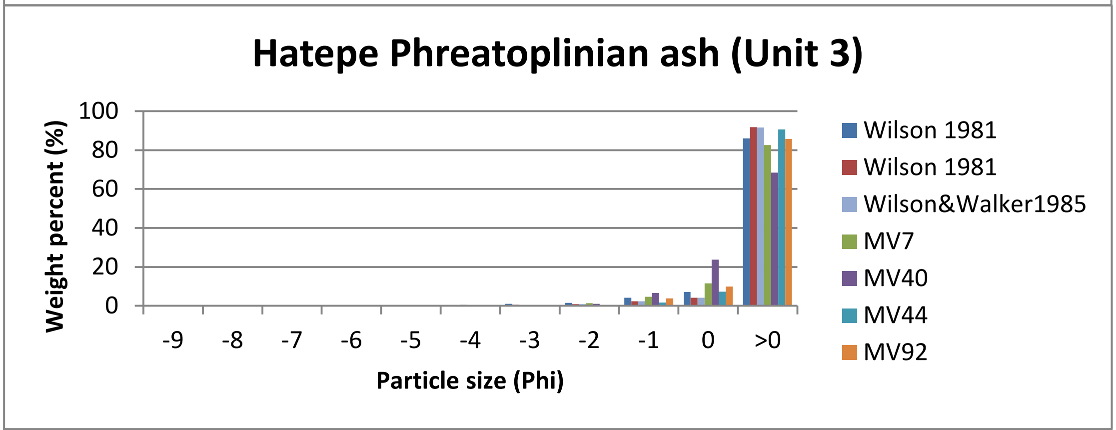
Name	Lenght (mm)	Diameter (mm)	Weight (g)	Volume m3
TVZ32	197	35.94	215.2	2.00E-04
TVZ34	174	35.73	193.3	1.74E-04
TVZ38	175	35.78	194.1	1.76E-04
TVZ39	175	35.84	194.8	1.77E-04
TVZ40	173	35.76	192.8	1.74E-04
TVZ42	199	35.4	215.8	1.96E-04
TVZ43	198	35.67	216.5	1.98E-04
TVZ44	197	35.66	213.6	1.97E-04
TVZ45	198	36.03	210.1	2.02E-04
TVZ46	199	36.02	219.7	2.03E-04
TVZ47	199	36.53	215.4	2.09E-04
TVZ48	199	35.67	215.5	1.99E-04
TVZ49	163	35.58	181.5	1.62E-04
TVZ50	158	35.71	175.9	1.58E-04
A01	159	35.46	175.7	1.56E-04
A04	174	35.65	193.1	1.73E-04
A05	198	36.31	215.3	2.05E-04
A07	174	35.64	193.4	1.73E-04
A08	198	35.85	219.3	2.00E-04
A09	174	35.70	193.9	1.74E-04
A10	174	35.65	195.1	1.74E-04
A11	200	35.84	209.9	2.01E-04
A12	202	34.71	216.3	1.91E-04
A13	198	35.71	216.4	1.98E-04
A14	175	35.67	195	1.74E-04
A15	198	36.02	222	2.01E-04
A16	175	35.69	195.5	1.75E-04
A18	175	35.63	193.6	1.74E-04
A21	200	35.21	215.2	1.94E-04

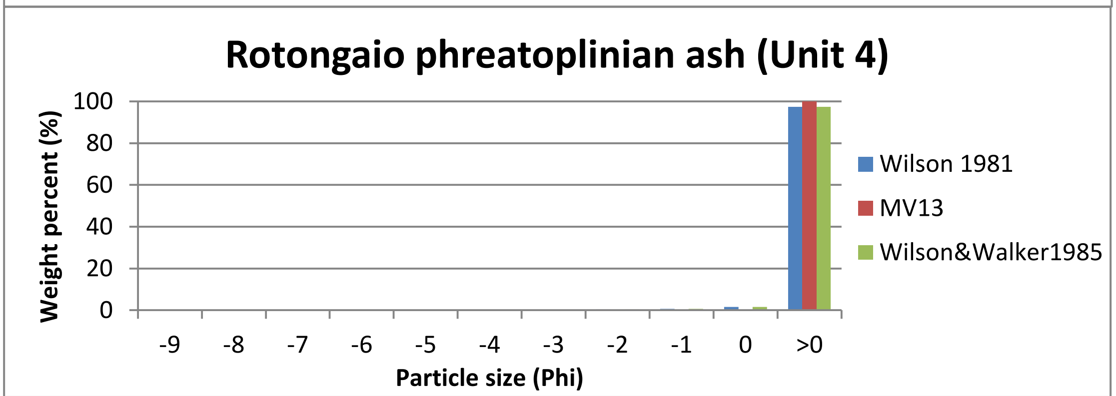
Appendix S: TAUPO ERUPTION DESCRIPTION

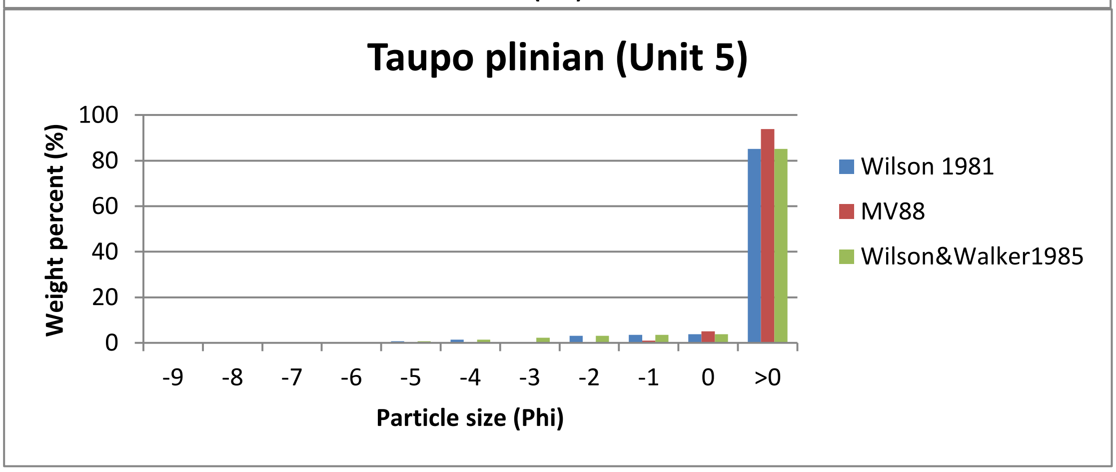
Unit	Unit Y	Origin and description	Volume Km3	Thickness
Source: Froggatt, 1980	Source: Wilson, 1993	Source: Froggatt, 1980 and Wilson, 1993	Source: Wilson, 1993	Source: Froggatt, 1980
Taupo Ignimbrite	Y7 Taupo ignimbrite	Ultra-plinian Pyroclastic flow triggered by caldera collapse and unroofing of the magma chamber	30	100m or more, thicker in valleys
	Y6 Early ignimbrite flow	Pyroclastic flow	1.5	
Taupo Lapilli	Y5 Taupo plinian pumice / Taupo lapilli	Plinian dry eruption Yellowish white, extremely angular, uniform, well sorted pumice lapilli and block beds Moderately vesicular pumice clasts (60-75% porosity).	7.7	Up to 2m (real thickness is unknown due to erosion by Y6)
Rotongaio Ash	Y4 Rotongaio ash	Phreatoplinian ;Wet fall Dark grey to black, fine to coarse ash Unconformably overlying hatepe ash Finely and regularly bedded	1.1	>6m
Hatepe tephra	Y3 Hatepe ash	Phreatoplinian Uniform fine white ash with scattered pumice lapilli Conformably overlying Y2 Bedding is commonly seen. Low lithic content	1.9	
	Y2 Hatepe plinian pumice, hatepe lapilli	Dry fall deposit minor magma water interaction Coarse white or pale yellow pumice lapilli, angular and moderately vesicular (porosity (60-70%). Small lithic content (<10%) Uniform, non-graded, well-sorted fall	2.5	
	Y1 Initial ash	Fall deposit	0.05	

Appendix T – Grain size population of the Taupo eruption comparison with other studies.

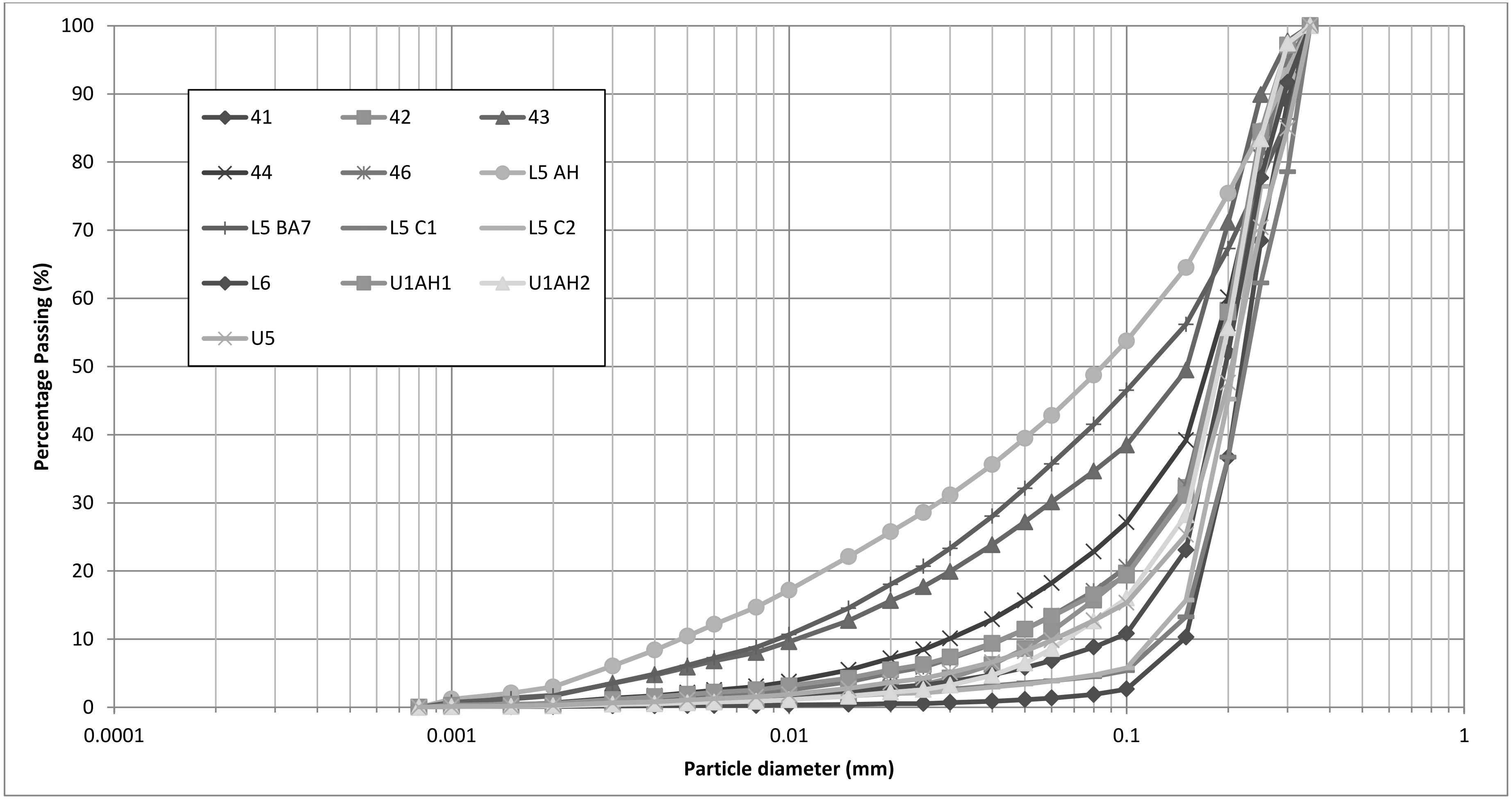








Appendix U – CHRISTCRHUCH LIQUEFACTION EJECTA PARTICLE SIZE DISTRIBUTION Source: Data from the analysis of Justin 2012



Appendix V: DETERMINATION OF THE LIQUID AND PLASTIC LIMITS, PLASTICITY INDEX AND WATER CONTENT

Test 2.5 from NZS 4402:1986: Determination of the cone penetration limit and water content

Test 2.3 from NZS 4402:1986: Determination of the plastic limit

Determination of the cone penetration limit and water content

(Test 2.5: NZS 4402:1986)

Sample no. MV56

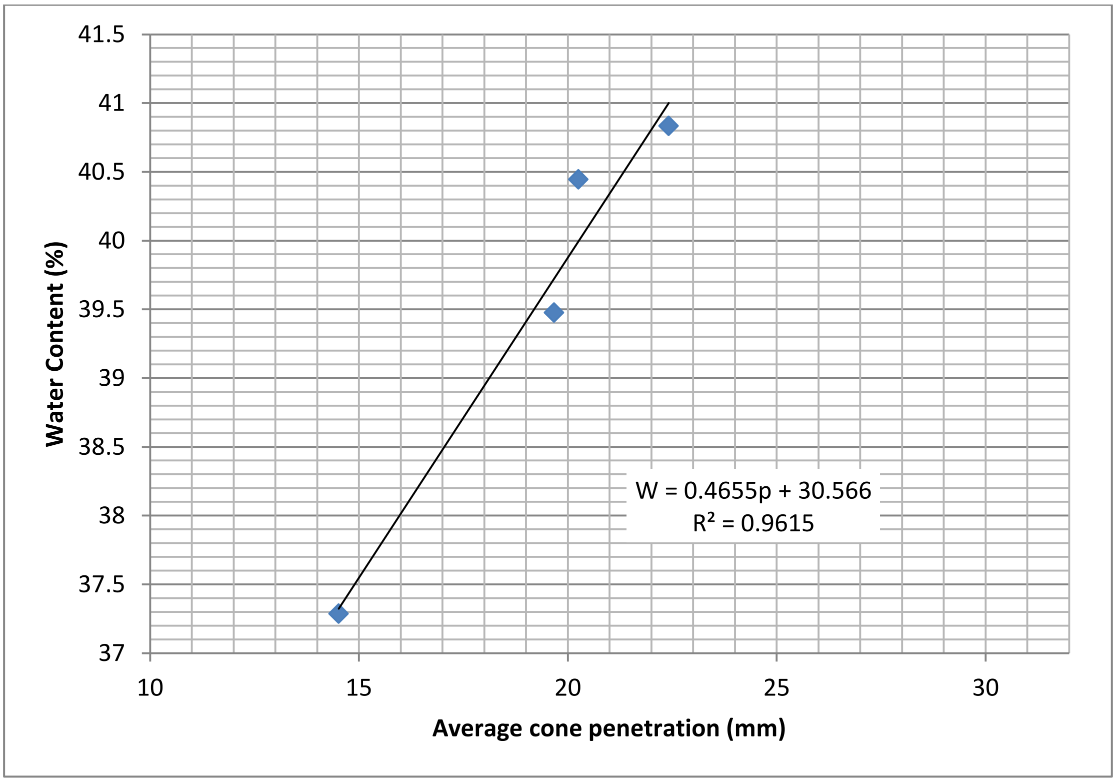
Test details:

Test performed on whole soil

History: air dried

Soil equilibrated with water for 16 hours

Test no.	1			2			3			4		
Initial dial gauge reading R1 mm	1.72	1.26	1.15	1.2	1.5	.87	.9	.88	1.5	1.29	1.76	
Final dial gauge reading R2 mm	16.29	15.95	15.45	21.1	20.8	20.69	21.8	20.56	21.24	23.85	24.03	
Cone penetration P = R2-R1 mm	14.57	14.68	14.3	18.9	18.3	19.82	20.9	19.68	20.19	22.56	22.27	
Average cone penetration mm	14.52			19.67			20.26			22.41		
Container number	K6			LS1			KARL4			LS11		
Mass of container and wet soil M2 g	55.065			71.988			65.606			69.981		
Mass of container and dried soil M3 g	48.691			60.572			55.854			58.859		
Mass of container M1 g	31.596			31.654			31.742			31.746		
Mass of water M2 – M3 g	6.374			11.416			9.752			11.086		
Mass of died soil M3 – M1 g	17.095			28.918			24.112			27.149		
Water content $w = \frac{M2-M3}{M3-M1}\ x\ 100$ %	37.29			39.48			40.44			40.83		



CPL (Water content at 20mm cone penetration): 39.876 40

Determination of the cone penetration limit and water content

(Test 2.5: NZS 4402:1986)

Sample no. S1

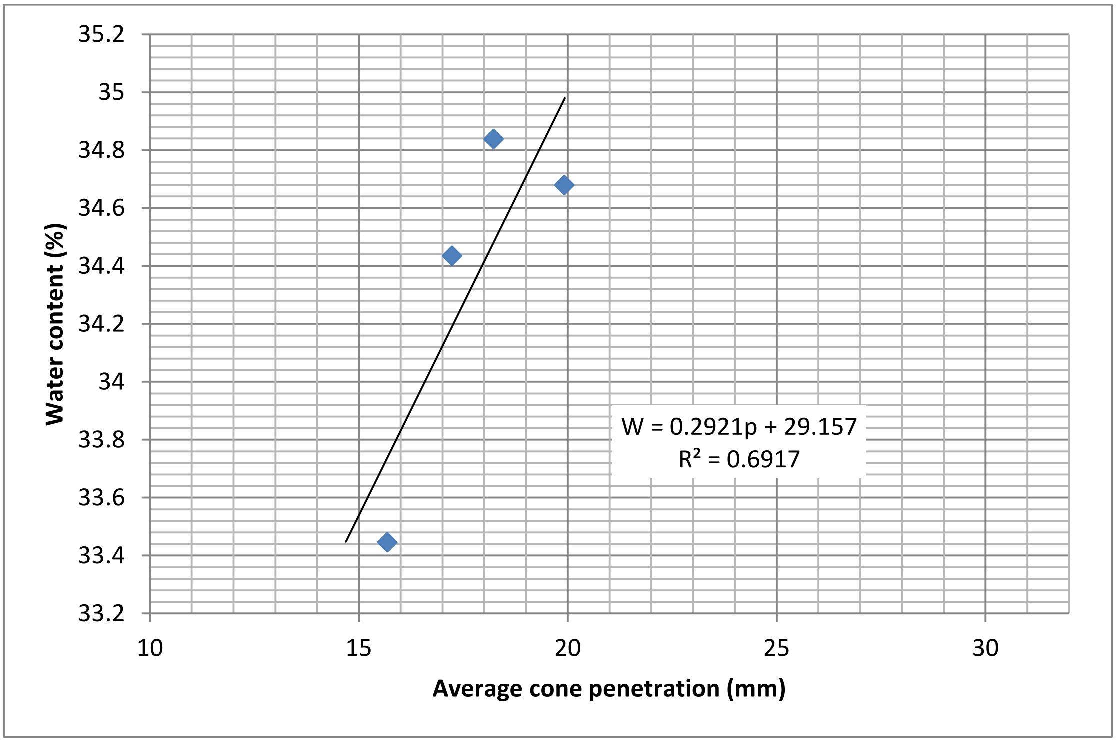
Test details:

Test performed on whole soil

History: natural

Soil equilibrated with water for 16 hours

Test no.	1			2			3			4		
Initial dial gauge reading R1 mm	.72	1.45	1.04	1.86	1.19		1.69	3.89		1.34	2.02	3.03
Final dial gauge reading R2 mm	19.16	19.41	19.34	21.26	21.65		19.05	21		18	16.66	18.8
Cone penetration P = R2-R1 mm	18.44	17.96	18.3	19.4	20.46	0	17.36	17.11	0	16.66	14.64	15.77
Average cone penetration mm	18.23			19.93			17.24			15.69		
Container number	F1			LS10			KARL1			H1		
Mass of container and wet soil M2 g	72.841			62.07			65.76			69.589		
Mass of container and dried soil M3 g	62.24			54.261			57.02			60.135		
Mass of container M1 g	31.81			31.743			31.638			31.868		
Mass of water M2 – M3 g	10.601			7.809			8.74			9.454		
Mass of died soil M3 – M1 g	30.43			22.518			25.382			28.267		
Water content $w = \frac{M2-M3}{M3-M1} x\ 100$ %	34.84			34.68			34.43			33.45		



CPL (Water content at 20mm cone penetration): 34.999 35

Determination of the plastic limit

(Test 2.3: NZS 4402:1986)

Sample no. MV56

Container number		K1	ET1
Mass of container and wet soil	M2 g	38.393	40.632
Mass of container and dried soil	M3 g	37.027	38.76
Mass of container	M1 g	31.89	31.706
Mass of water	M2 – M3 g	1.366	1.872
Mass of died soil	M3 – M1 g	5.137	7.054
Water content $w = \frac{M2-M3}{M3-M1}\ x\ 100$	%	26.59	26.56
Plastic Limit		27	

Sample no. S1

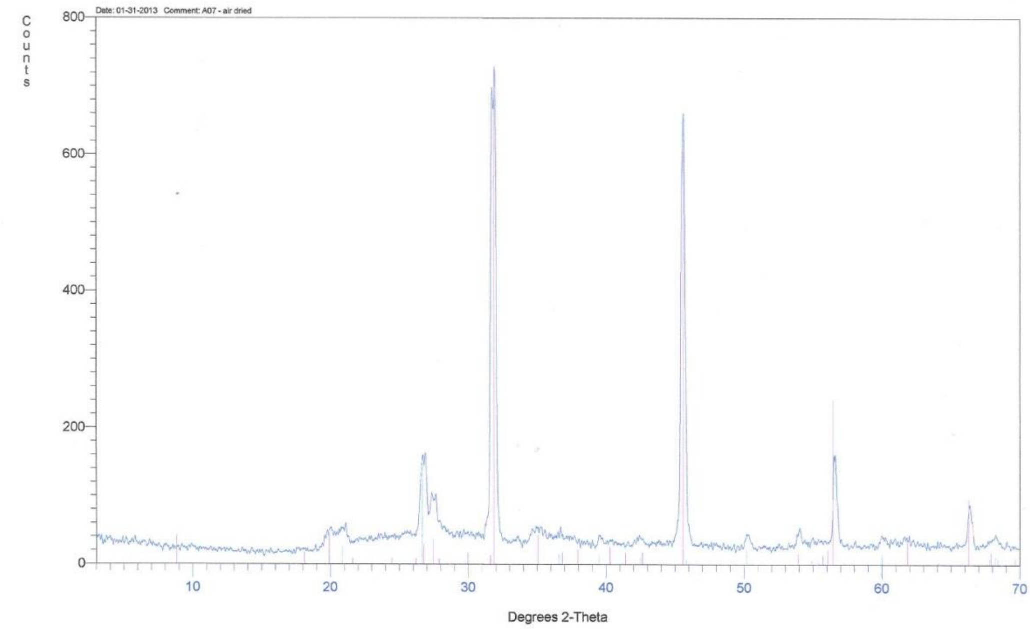
Container number		DORD CP2	9
Mass of container and wet soil	M2 g	34.134	35.04
Mass of container and dried soil	M3 g	33.543	34.351
Mass of container	M1 g	31.403	31.861
Mass of water	M2 – M3 g	0.591	0.689
Mass of died soil	M3 – M1 g	2.14	2.49
Water content $w = \frac{M2-M3}{M3-M1}\ x\ 100$	%	27.62	27.67
Plastic Limit		28	

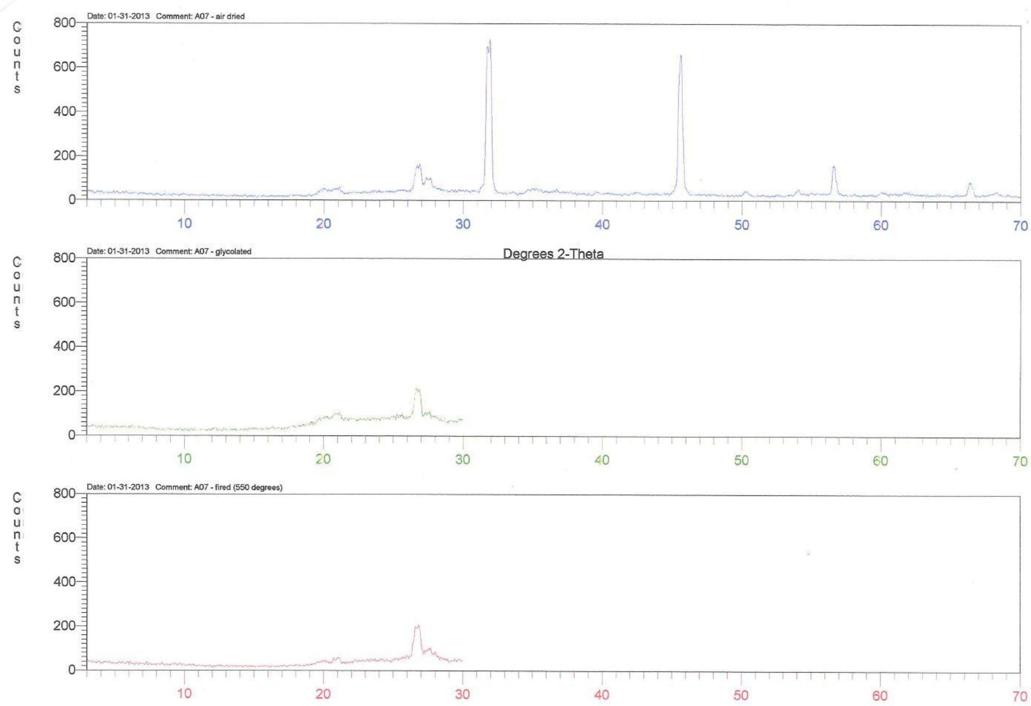
Appendix W – X-RAY DIFFRACTION (XRD) SCANS RESULTS

W.1: Database line colour reference

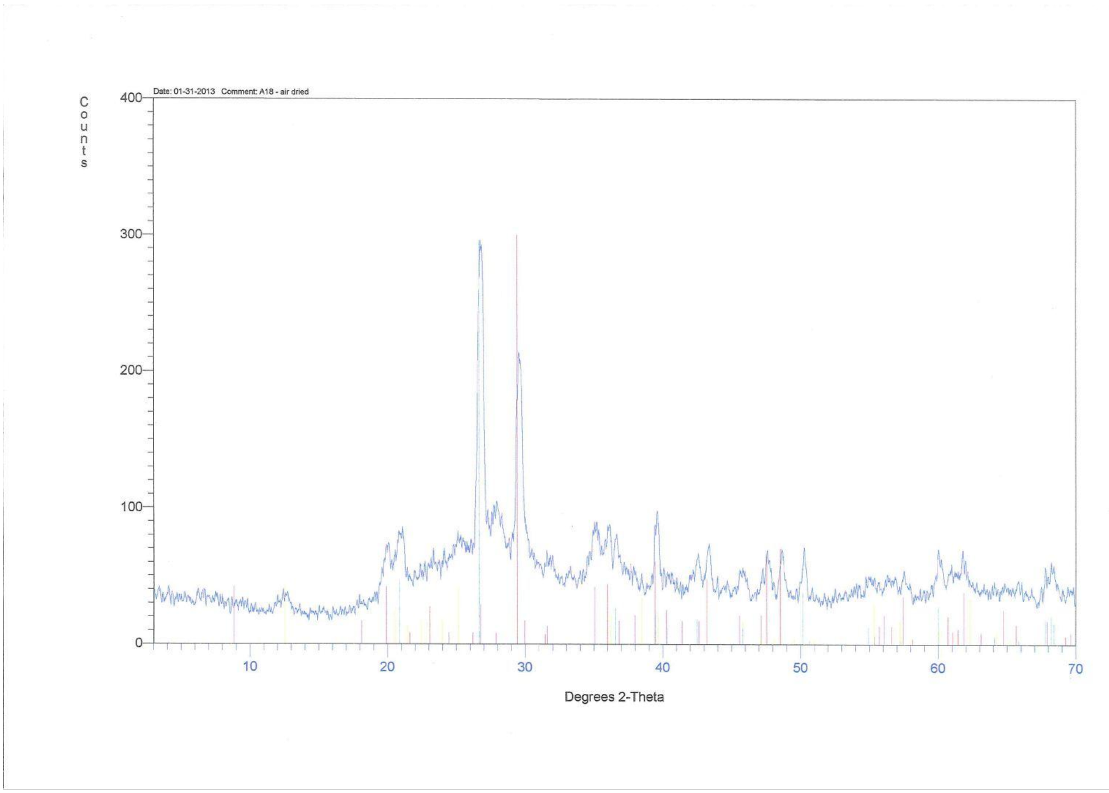
QUARTZ	ALBITE	KAOLINITE	ILLITE-MONTMORILLONITE	ILLITE	CALCITE	HALITE
BLUE	GREEN	YELLOW	BLACK	PURPLE	RED	PINK

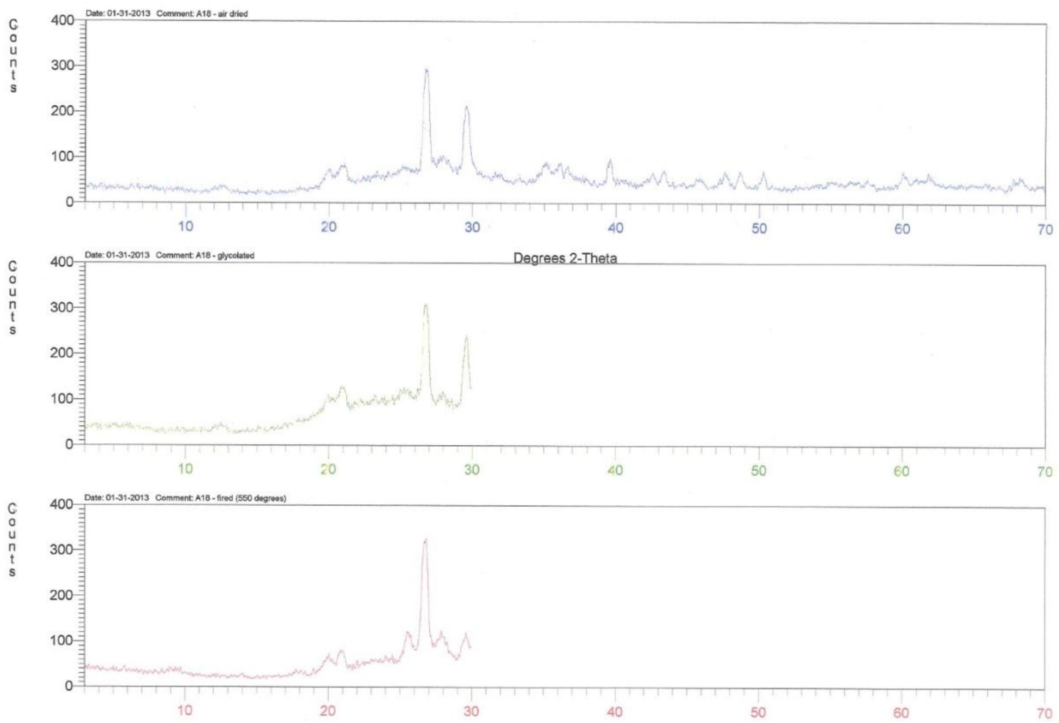
W.2 - A07


Date: 01-31-2013 Comment: A07 - air dried
Counts
800
600
400
200
0
10
20
30
40
50
60
70
Degrees 2-Theta

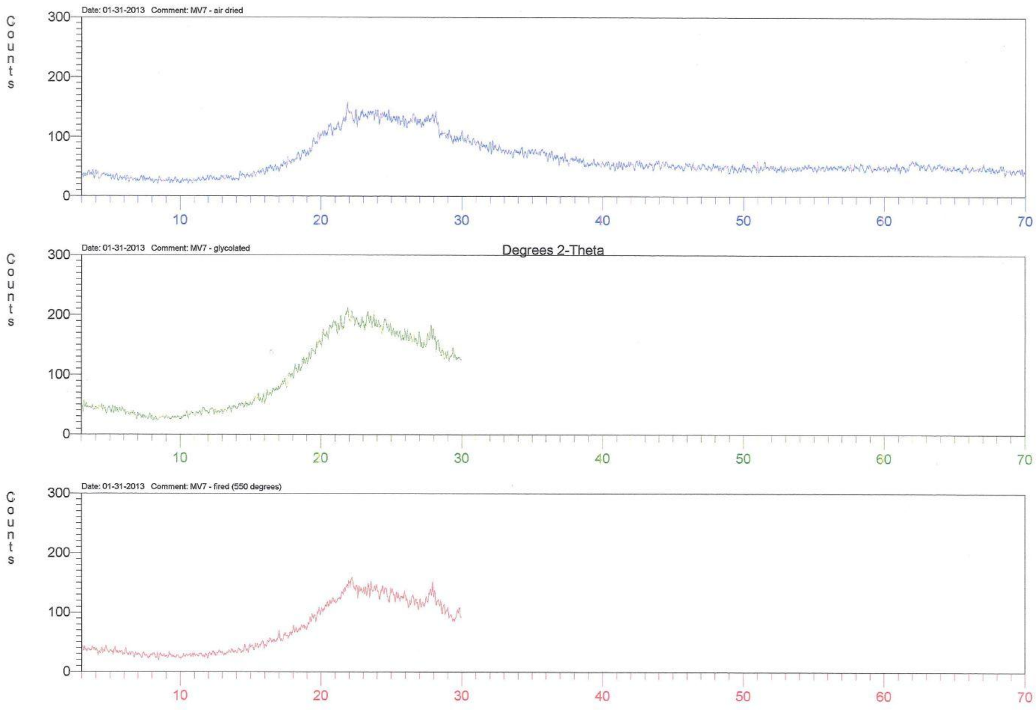

Date: 01-31-2013 Comment: A07 - air dried
Counts
800
600
400
200
0
10
20
30
40
50
60
70
Degrees 2-Theta
Date: 01-31-2013 Comment: A07 - glycolated
Counts
800
600
400
200
0
10
20
30
40
50
60
70
Date: 01-31-2013 Comment: A07 - fired (550 degrees)
Counts
800
600
400
200
0
10
20
30
40
50
60
70

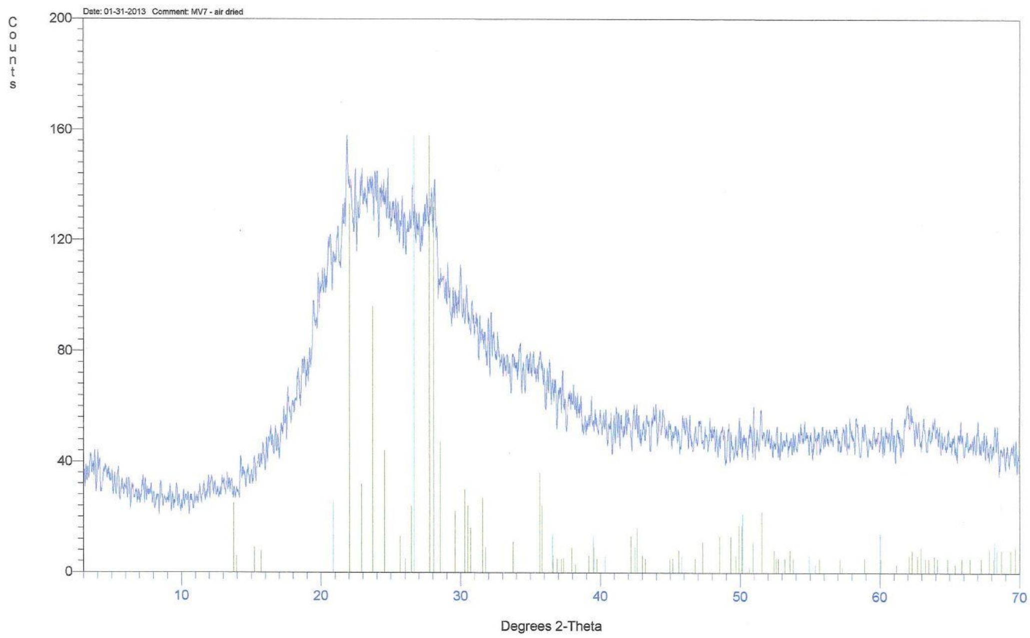
W.3 - A18


Date: 01-31-2013 Comment: A18 - air dried
Counts
400
300
200
100
0
10
20
30
40
50
60
70
Degrees 2-Theta

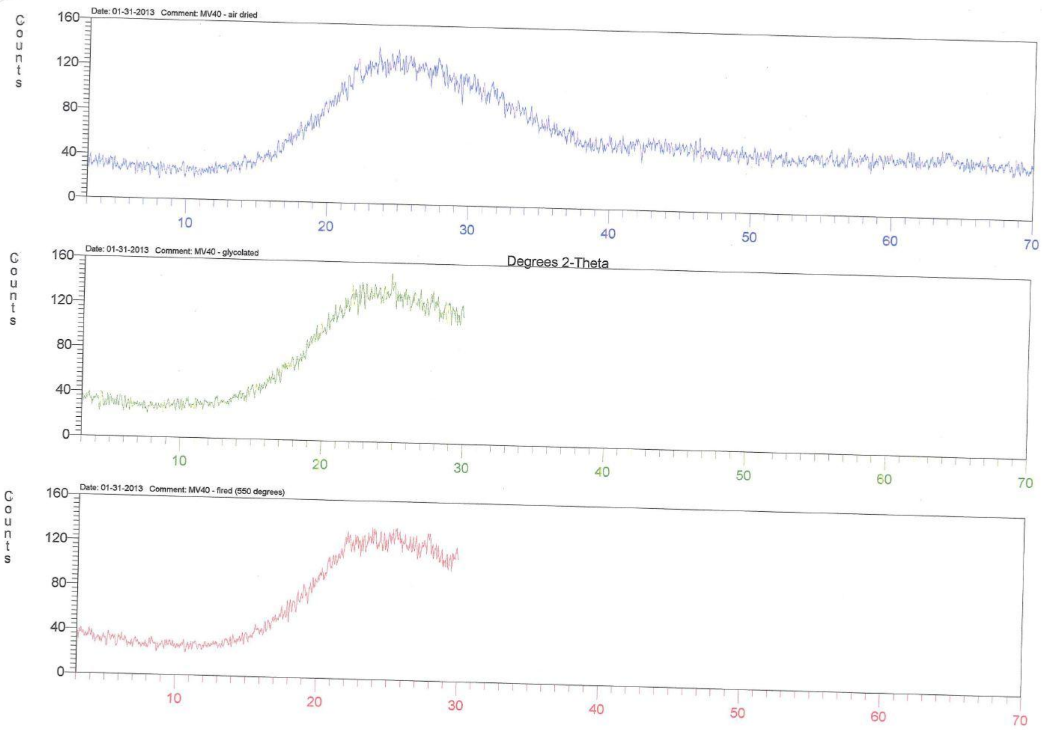

Date: 01-31-2013 Comment: A18 - air dried
Counts
Degrees 2-Theta
Date: 01-31-2013 Comment: A18 - glycolated
Date: 01-31-2013 Comment: A18 - fired (550 degrees)

W.4 - MV7

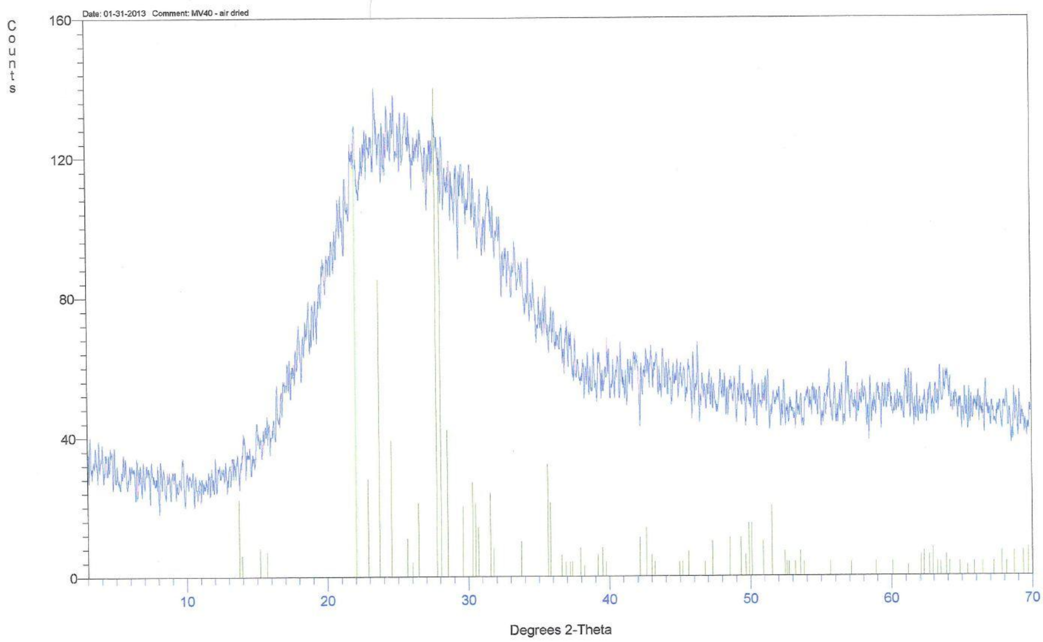

Date: 01-31-2013 Comment: MV7 - air dried
Counts
300
200
100
0
10
20
30
40
50
60
70
Degrees 2-Theta
Date: 01-31-2013 Comment: MV7 - glycolated
Counts
300
200
100
0
10
20
30
40
50
60
70
Date: 01-31-2013 Comment: MV7 - fired (550 degrees)
Counts
300
200
100
0
10
20
30
40
50
60
70


Date: 01-31-2013 Comment: MV7 - air dried
Counts
200
160
120
80
40
0
10
20
30
40
50
60
70
Degrees 2-Theta

W.5 - MV40

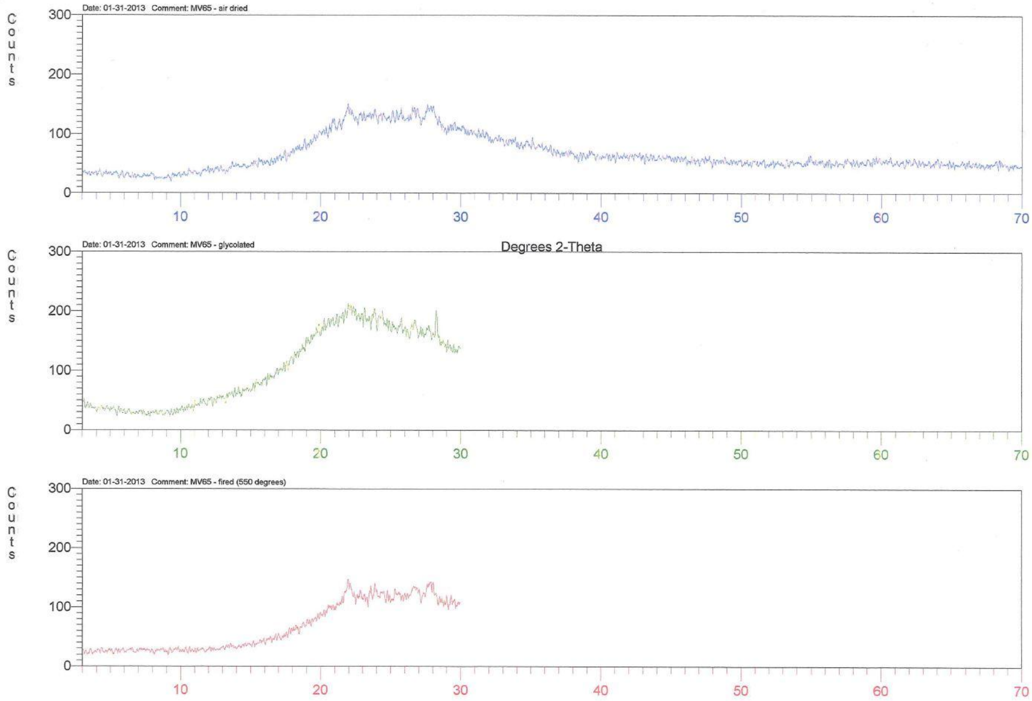


Date: 01-31-2013 Comment: MV40 - air dried
Date: 01-31-2013 Comment: MV40 - glycolated
Date: 01-31-2013 Comment: MV40 - fired (550 degrees)
Counts
Degrees 2-Theta

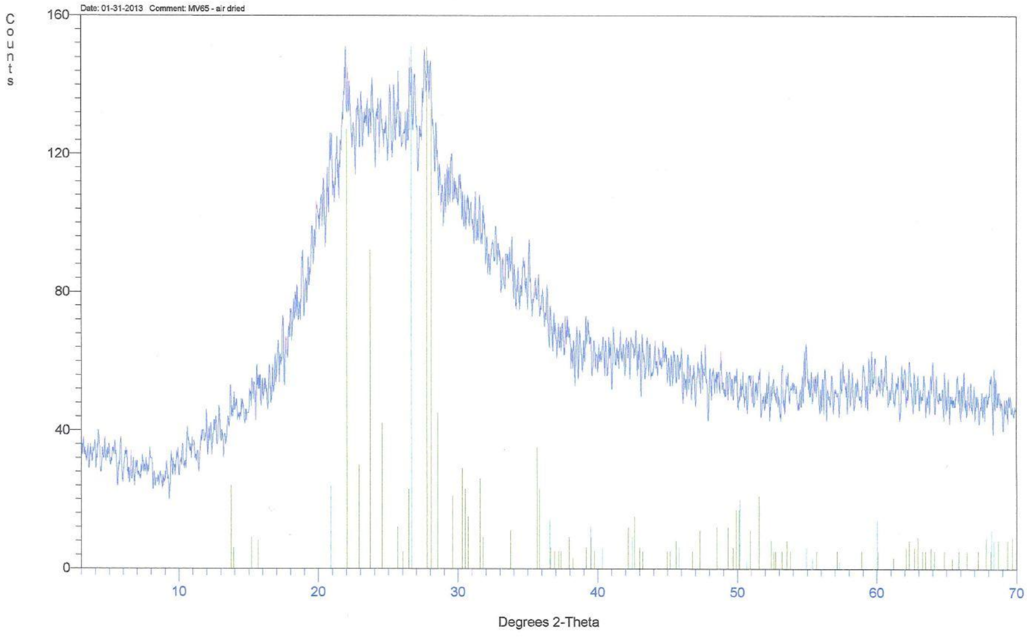


Date: 01-31-2013 Comment: MV40 - air dried
Counts
Degrees 2-Theta

W.6 - MV65

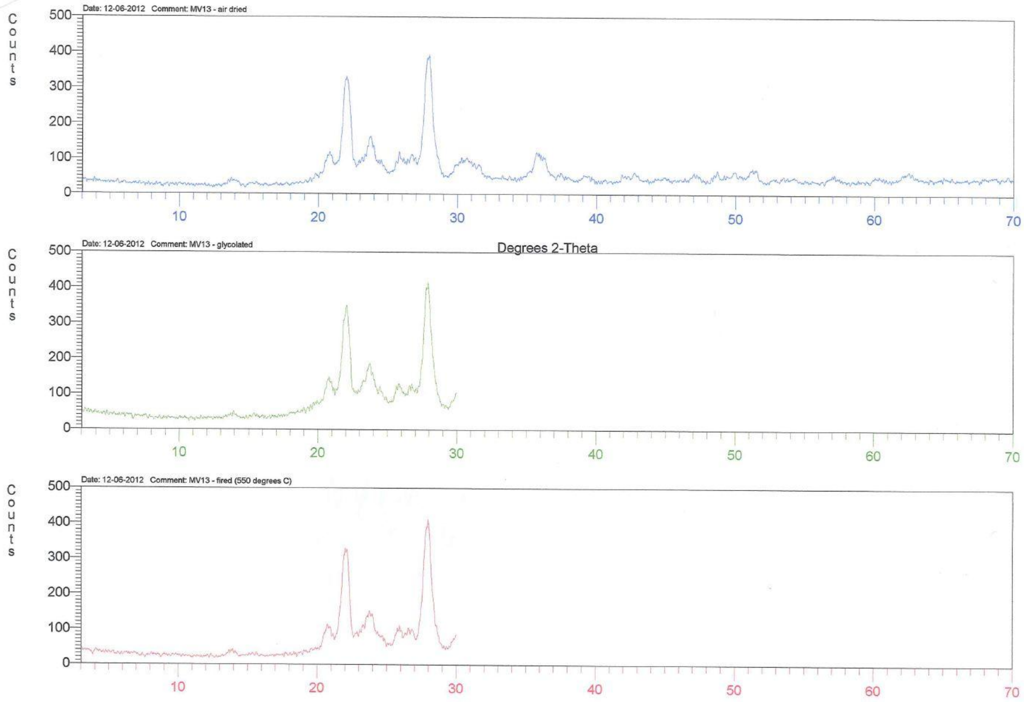


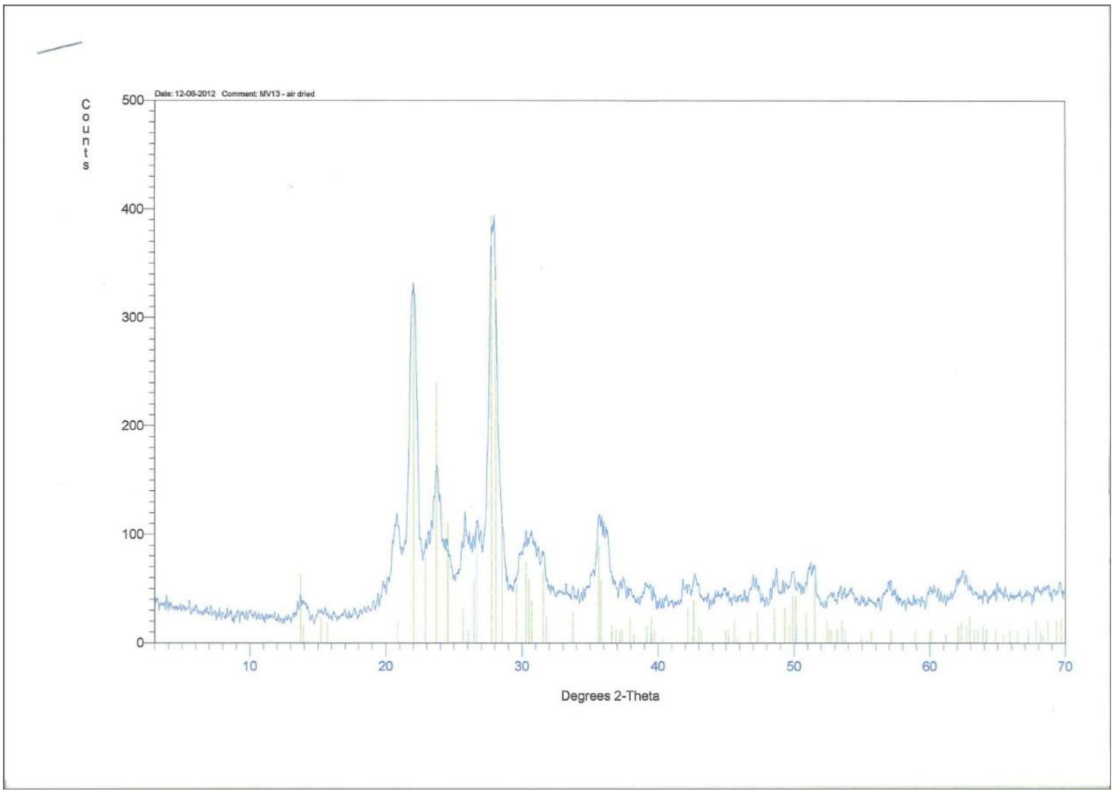
Date: 01-31-2013 Comment: MV65 - air dried
Counts
Degrees 2-Theta
Date: 01-31-2013 Comment: MV65 - glycolated
Date: 01-31-2013 Comment: MV65 - fired (550 degrees)



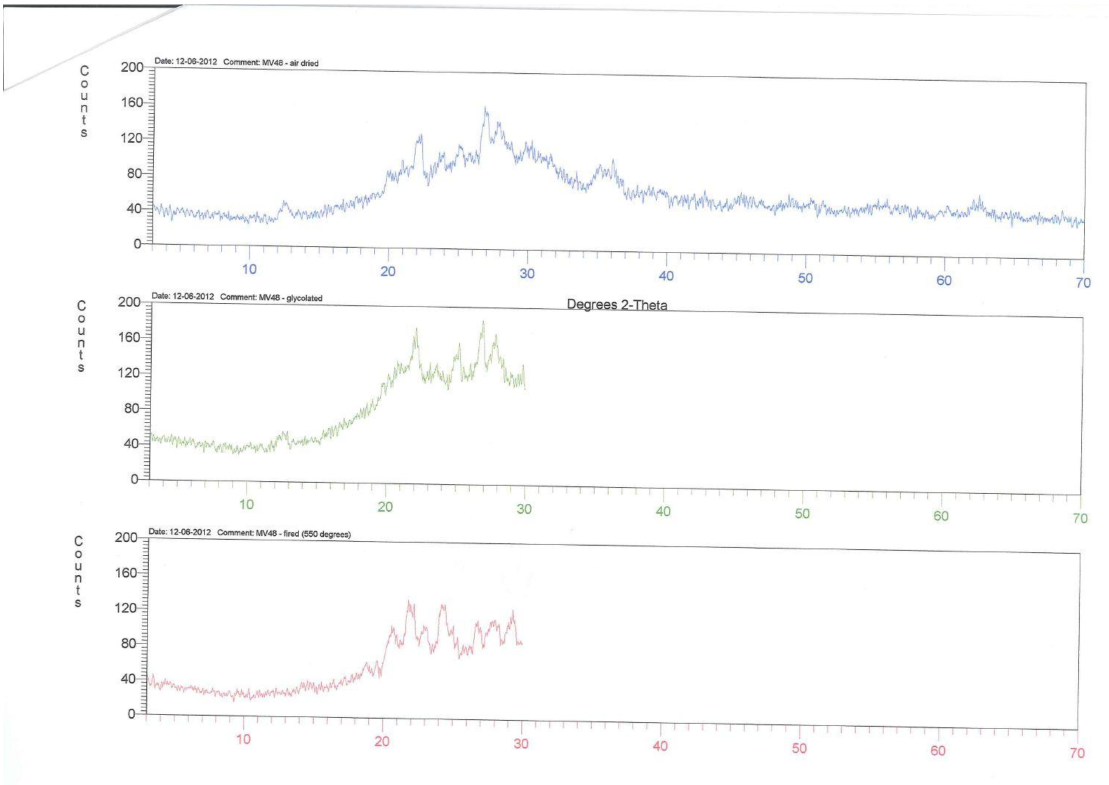
Date: 01-31-2013 Comment: MV65 - air dried
Counts
Degrees 2-Theta

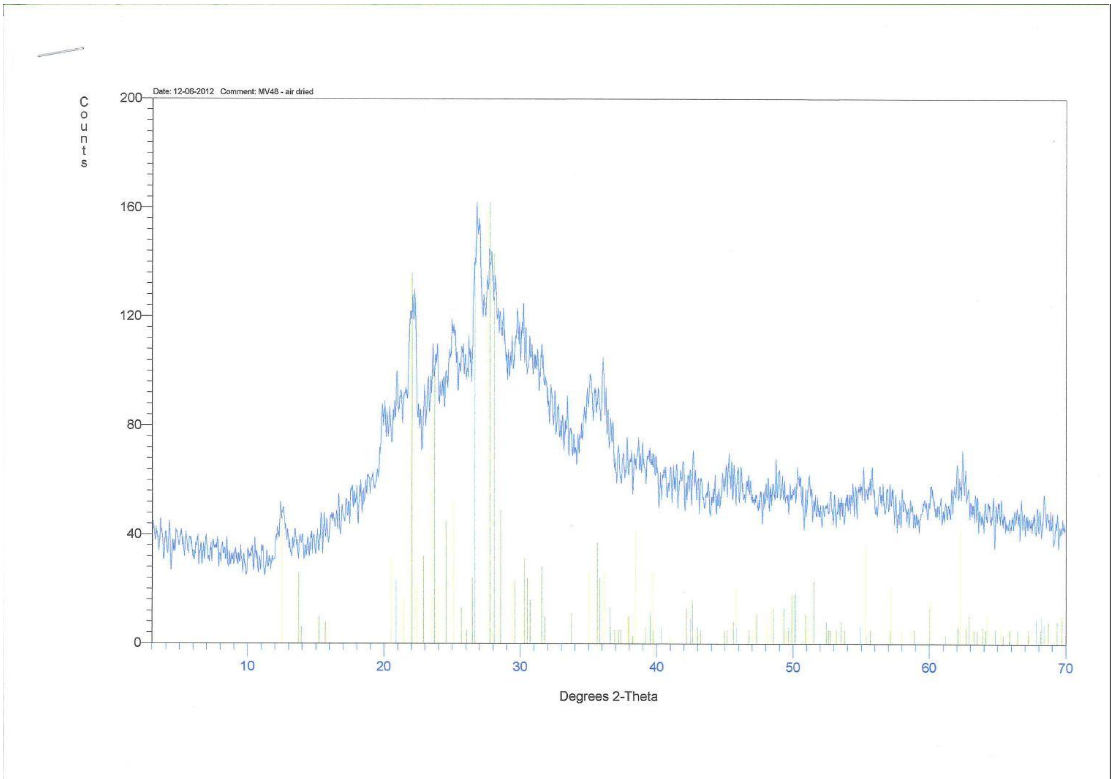
W.7 - MV13


Date: 12-06-2012 Comment: MV13 - air dried
Counts
Degrees 2-Theta
Date: 12-06-2012 Comment: MV13 - glycolated
Counts
Date: 12-06-2012 Comment: MV13 - fired (550 degrees C)
Counts

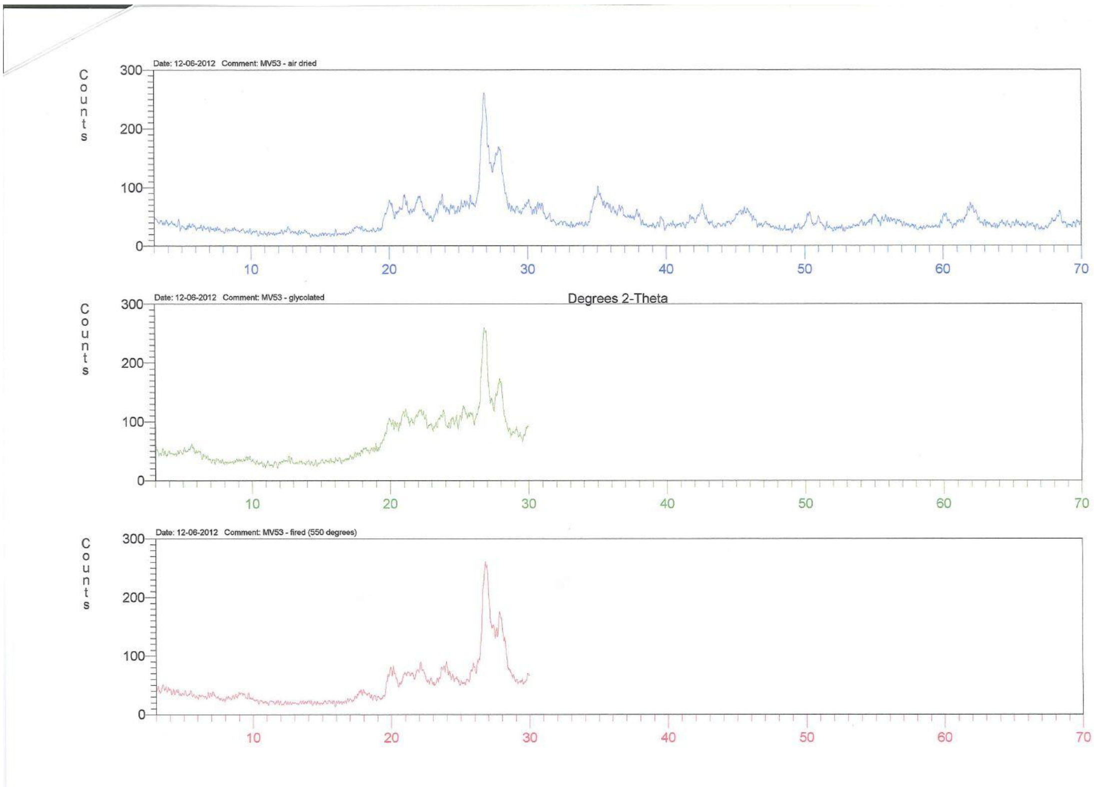

Date: 12-06-2012 Comment: MV13 - air dried
Counts
Degrees 2-Theta

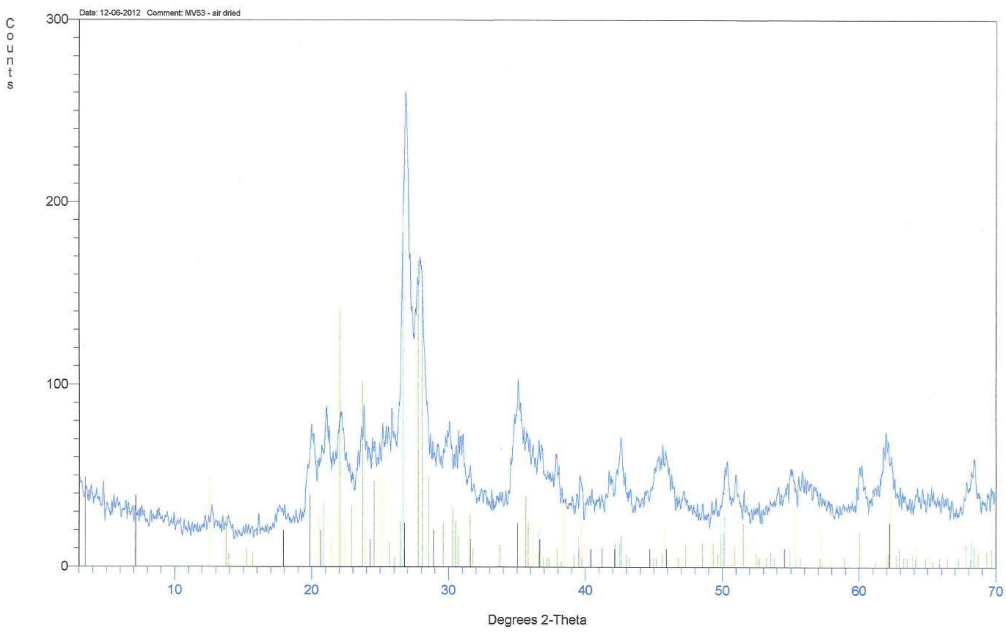
W.8 - MV48


Date: 12-06-2012 Comment: MV48 - air dried
Counts
Degrees 2-Theta
Date: 12-06-2012 Comment: MV48 - glycolated
Counts
Date: 12-06-2012 Comment: MV48 - fired (550 degrees)
Counts

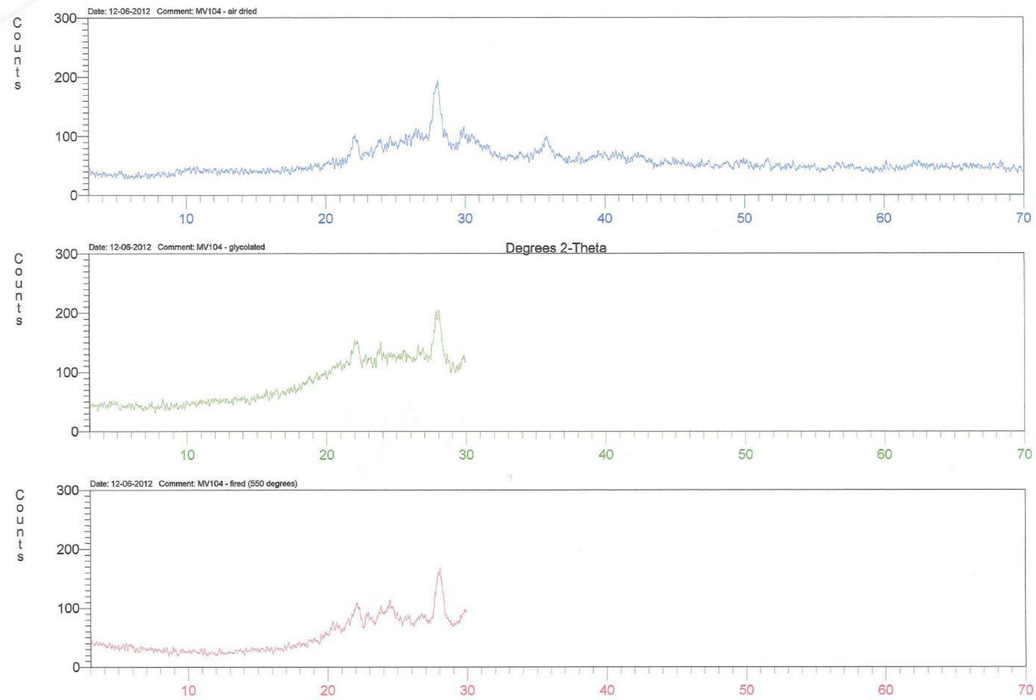

Date: 12-06-2012 Comment: MV48 - air dried
Counts
Degrees 2-Theta

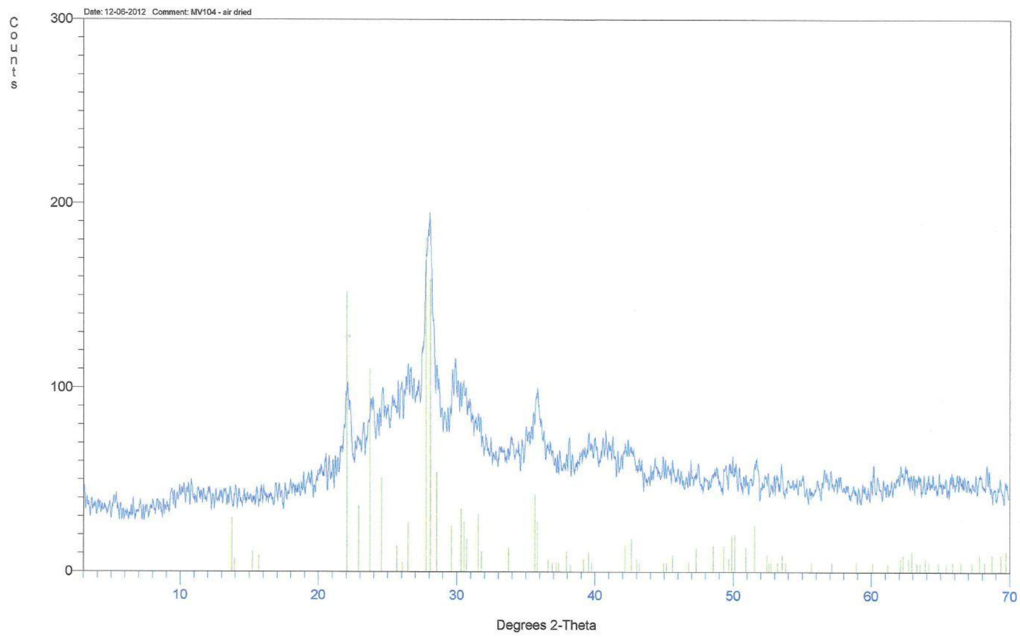
W.9 – MV53


Date: 12-06-2012 Comment: MV53 - air dried
Counts
300
200
100
0
10
20
30
40
50
60
70
Degrees 2-Theta
Date: 12-06-2012 Comment: MV53 - glycolated
Counts
300
200
100
0
10
20
30
40
50
60
70
Date: 12-06-2012 Comment: MV53 - fired (550 degrees)
Counts
300
200
100
0
10
20
30
40
50
60
70


Date: 12-06-2012 Comment: MV53 - air dried
Counts
300
200
100
0
10
20
30
40
50
60
70
Degrees 2-Theta

W.10 – MV104


Date: 12-06-2012 Comment: MV104 - air dried
Counts
Degrees 2-Theta
Date: 12-06-2012 Comment: MV104 - glycolated
Date: 12-06-2012 Comment: MV104 - fired (550 degrees)


Date: 12-06-2012 Comment: MV104 - air dried
Counts
Degrees 2-Theta

Appendix X : Grain size analysis results (Attached CD)

Appendix Y : GIS data master sheets (Attached CD)